

Does increasing soil carbon in sandy soils increase soil nitrous oxide emissions from grain production?

Lead organisation and partner organisations: The University of Western Australia and the Department of Agriculture and Food, Western Australia.

Primary contact and contact details: Dr Louise Barton, School of Earth and Environment, The University of Western Australia, 35 Stirling Highway, Crawley 6009.

Email: louise.barton@uwa.edu

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Executive Summary

Increasing soil organic carbon is promoted as a strategy for sequestering carbon dioxide and mitigating anthropogenic greenhouse gas emissions. International research demonstrates increasing soil organic carbon benefits crop productivity, but also enhances other greenhouse gas emissions including nitrous oxide and methane.

Our 2.5 year field-based study concluded that land management practises that increase soil organic carbon in Western Australia's sandy cropping soils should be encouraged. Increasing soil organic carbon benefited grain yield and increased plant available nitrogen, and showed potential to decrease nitrogen fertiliser inputs.

Although increasing soil organic carbon increased soil nitrous oxide emissions (and inhibited methane uptake), losses were modest (0.08–0.12% of applied nitrogen fertiliser) and significantly less than the international default value (1.0%).

This finding, and past research in south-western Australia, supports lowering Australia's current emission factor (0.3%) for calculating nitrous oxide losses from the application of nitrogen fertiliser to rainfed cropping soils in Australia's semi-arid regions.

Growers should also be encouraged to modify nitrogen fertiliser inputs to reflect changes in plant available nitrogen resulting from improvements in soil organic carbon. This will require fertiliser decision support models to accurately predict soil nitrogen supply. Optimising nitrogen fertiliser inputs will increase profitability for growers, plus minimise soil nitrous oxide emissions.

Background

Increasing soil organic carbon (SOC) is promoted as a strategy for sequestering carbon dioxide (CO₂) and mitigating anthropogenic greenhouse gas (GHG) emissions. Agricultural management practices such as the conversion from conventional to no-till or reduced tillage, residue retention and addition, and crop rotations have been shown to have the potential to increase SOC (Smith et al., 2000; Luo et al., 2010; Liu et al., 2014). It is estimated that widespread adoption of these recommended practices would increase SOC in croplands by 0.4 to 0.8 Pg C per year globally (Lal, 2004), with up to 0.99 Pg C in Australia cropping soils (Lam et al., 2013; Luo et al., 2014). However, while these agricultural practices may benefit soil carbon (C) sequestration, their contribution to mitigating global climate warming may be offset by emissions of other GHGs (Six et al., 2004; Liu et al., 2014).

Increasing SOC can increase nitrous oxide (N₂O) emissions, a potent GHG, by increasing the availability of nitrogen (N) and C to soil microorganisms. Crop residues are subject to N mineralisation, and in turn nitrification and denitrification; microbial processes that lead to N₂O production (Butterbach-Bahl et al., 2013). For example, nitrifying microbes convert soil ammonium (NH₄⁺) to nitrate (NO₃⁻) under aerobic conditions, which may result in N₂O-formation as a by-product of the N transformation. Likewise, anaerobic denitrifiers sequentially reduce nitrogen oxides (e.g. NO₃⁻) to nitric oxide, N₂O and finally N₂; with N₂O emissions resulting from an incomplete conversion. Increasing soil N concentrations also inhibits methane (CH₄) uptake by soil (Le Mer and Roger, 2001). While soil C sequestration would be expected to reach a maximum threshold, the effects on soil N₂O and CH₄ emissions could continue if SOC concentrations were maintained. Understanding the interaction between increasing SOC and GHG emissions is critical when assessing the effectiveness of land management practices to abate GHG emissions from the agricultural land sector.

Increasing SOC can also increase crop production and has the potential to lower the amount of N fertiliser required for crop production. International meta-analyses have demonstrated the incorporation of straw and crop residues into soil benefited crop yield with time by improving plant nutrient availability [N, phosphorous (P) and potassium (K)] and soil physical conditions (Chen et al., 2013; Lehtinen et al., 2014; Liu et al., 2014). Realising the benefits of increased SOC on plant nutrient availability would benefit Australia growers as fertiliser application is the largest single variable expense for grain production. Better matching N fertiliser inputs to crop demand not only increases cropping profitability, but also decreases the risk of soil N₂O emissions. Understanding how increasing SOC influences N fertiliser requirements would further optimise N fertiliser use, and minimise N₂O emissions, from grain production.

The effect of increasing SOC on GHG emissions and N fertiliser requirements is poorly understood for Australia's infertile dryland cropping soils. Our knowledge of the interaction between soil C and GHG emissions is mainly derived from agricultural systems in the Northern Hemisphere (Stehfest and Bouwman, 2006; Chen et al., 2013; Lehtinen et al., 2014; Liu et al., 2014). The majority of studies have investigated these effects on medium fertility soils, with GHG emissions often measured for only one to two growing seasons (Liu et al., 2014). The overall objective of this project was to investigate whether increasing SOC altered GHG emissions (N₂O and CH₄) and N fertiliser requirements for crop production in a sandy soil in south-western Australia. We hypothesized that increasing SOC would increase soil N₂O and CH₄ emissions, but at the same time lower the amount of N fertiliser required for grain production.

Methodology

Assessing the effect of soil carbon on N₂O emissions

A key question investigated by the research project was: Does increasing SOC alter N₂O emissions? The following section outlines the methods and activities that were undertaken to address this question.

Study site

We investigated whether increasing SOC altered N₂O and methane (CH₄) emissions at the Liebe Group's Long Term Research Site at Buntine (30° 54' S, 116° 21' E; elevation of 315 m), in the northern grain belt of Western Australia, approximately 296 km north-east of Perth. The site was established in 2003, and included a variety of replicated treatments aimed at altering SOC concentrations. The current study used field plots amended with (OM+tillage) or without (Tillage) the addition of organic matter (OM) every three years, with both treatments tilled annually. The most recent application of OM (20 t ha⁻¹ of chaff) was in 2012, with a total of 80 t ha⁻¹ applied to the OM+tillage treatments since the study site was established. During the present study, SOC (0–100 mm) averaged 1.20% in the plus OM treatment versus 0.64% in the no OM treatment.

The study site was located in a semi-arid region of Western Australia. The nearby town of Dalwallinu has an annual rainfall of 285 mm, a mean daily maximum temperature of 26.2 °C and a mean daily minimum temperature of 11.6 °C [calculated using data collected from the past 15 years (1997 to 2012); Commonwealth Bureau of Meteorology, <http://www.bom.gov.au/climate/averages>]. The soil at the experimental site consisted of a free-draining sand (Basic Regolithic Yellow-Orthic Tenosol; Isbell, 2002) and was located on flat to gently undulating land (Table 1). The land-use history of the site for the five years prior to commencing this study was: 2007, wheat (sprayed out due to drought and weeds); 2008, wheat; 2009, lupin; 2010, wheat; 2011, wheat. The site was exclusively cropped, and not grazed by farm animals, following its establishment in 2003.

Table 1. Selected soil properties (0–100 mm) for treatments at the Buntine, Western Australia. Values are means (and standard errors) of at least six replicates.

Soil property	OM+tillage	Tillage
Nitrogen (%)	0.10 (0.01)	0.06 (0.00)
pH (0.01M CaCl ₂)	6.20 (0.1)	6.31 (0.1)
Electrical conductivity (μS cm ⁻¹)	216 (25)	136 (6.8)
Cation exchange capacity (cmol (+) kg ⁻¹)	4.19 (0.3)	2.28 (0.1)
Silt (%)	3.2 (0.3)	2.2 (0.2)
Clay (%)	6.4 (0.2)	4.9 (0.2)
Sand (%)	90.4 (0.1)	92.9 (0.2)
Field capacity (g H ₂ O cm ⁻³)	0.39 (1.0)	0.33 (1.7)

Experimental design and approach

A randomised-split plot design, with three replicates was employed at the study site. Two blocks (OM+tillage, Tillage) were divided into six plots (41 m²), with half the plots receiving N fertiliser and the remaining plots receiving no N fertiliser. Plots were planted to canola (*Brassica napus* cv CBWA Telfer) on 6 June 2012, barley (*Hordeum vulgare* cv Hindmarsh) on 5 June 2013, and oats (*Avena sativa* cv Brusher) on 6 May 2014. Plots received 40 kg ha⁻¹ of triple superphosphate inserted to a soil depth of 30 mm at planting in 2012 and 2013, and

no fertiliser at planting in 2014. Half the plots in each OM treatment then received a surface application of urea (100 kg N ha⁻¹) four weeks after seeding (10 July 2012, 3 July 2013, 3 June 2014). The N fertiliser application rate was greater than that typically applied by growers in the district so as provide the greatest potential for N₂O emissions.

Measurement of N₂O and CH₄ fluxes

Gaseous soil fluxes were measured for approximately 2.5 years, and commenced 7 June 2012 following planting. Fluxes were measured in each treatment plot using soil chambers (one per plot) connected to a fully automated system that enabled simultaneous determination of N₂O and CH₄ fluxes (Breuer et al., 2000; Kiese et al., 2003). Briefly, the system consisted of a gas chromatograph (Texas Instruments, SRI 8610C) fitted with a ⁶³Ni electron capture detector for N₂O analyses, a flame ionisation detector for CH₄ analyses, an automated sampling unit for collecting and distributing gas samples, and 12 chambers (one per treatment plot). Chambers (500 mm x 500 mm; clear perspex) were placed on metal bases inserted into the ground (100 mm), and fitted with a top that automatically opened and closed. Four bases were located in each treatment plot to enable the chambers to be moved to a new position every week so as to minimise the effect of chambers on soil properties and plant growth. The height of the chambers (not bases) was progressively increased with clear perspex extensions to accommodate crop growth, with a minimum height of 150 mm and a maximum height of 950 mm. The detection limits were estimated to be 0.6 µg N₂O-N m⁻² h⁻¹ for N₂O and 4 µg CH₄-C m⁻² h⁻¹ for CH₄ at a chamber height of 150 mm, and the dilution via leakage was considered negligible.

The automated gas sampling unit enabled N₂O and CH₄ fluxes to be monitored continuously, providing up to eight (hourly) fluxes per day. A full measurement cycle (3 h) consisted of measuring fluxes from four chambers at a time, followed by the next four chambers and then the final four chambers. The system was automatically calibrated by standard calibration gases (e.g., 0.5 µL L⁻¹ N₂O, 3.9–4.0 µL L⁻¹ CH₄, depending on the calibration cylinder; with a variance +/- 5% of each component) during the measurement cycle. Within a set of four chambers, gas samples were collected sequentially from each chamber immediately following chamber enclosure, with a total of four gas samples per chamber, plus four standard calibration samples, analysed for N₂O and CH₄ during a 60 minute interval; chamber lids re-opened immediately after the last sample was collected for the set of chambers. Consequently, the chambers remained open for at least 126 min between each measurement cycle. The chambers were programmed to open if the air temperature in the chamber exceeded a set value (e.g., 42°C during growing season, 60°C at other times) or if it rained (> 0.4 mm in five minutes) while the chambers were closed.

Soil properties with time

Soil mineral N [nitrate (NO₃⁻) and ammonium (NH₄⁺)], dissolved organic C, and volumetric water content (VWC) were measured to explain seasonal variations in N₂O fluxes. The mineral N of the surface soil (0–100 mm) was measured immediately before planting and then 7 and 14 days following planting or the application of N fertiliser. From then onwards, samples were collected every four weeks. One sample was collected from each plot at each sampling date, with each sample containing four combined subsamples. Every four weeks soil samples were also analysed for dissolved organic C.

Nitrate and NH₄⁺ were extracted from soil samples by adding 80 mL of 1 M potassium chloride to 20 g of sieved (< 4 mm) field-moist soil and shaking for 1 h. The filtered solution (Filtech No. 282, Filtech Specialised Products, Adelaide, Australia) was frozen until analysis

for NH_4^+ and NO_3^- (plus NO_2^-) colorimetrically using a Berthelot reaction for NH_4^+ and the hydrazinium reduction method for NO_3^- on a Skalar San Plus auto-analyser (Skalar Inc., Breda, The Netherlands) (Downes, 1978). Dissolved organic C was measured by further filtering the mineral N extract through a polyethersulfone membrane (45 μm pore size; Pall Gelman Laboratory, Michigan, USA; Sarstedt, Nümbrecht, Germany) and analysing for total oxidisable C (Shimadzu, TOC-5000A). Gravimetric soil water content was determined at the same time that soil samples are collected for mineral N analysis, and after drying sub-samples at 105°C for at least 24 h.

The soil VWC was measured continuously using moisture probes (MP-406, ICT International, Armidale, Australia) inserted in eight of the 12 plots (i.e., 2 replicates per treatments) at a depth of 100 mm. Values were collected and stored every 30 minutes using a data logger (SL5 Smart Logger, ICT International, Armidale, Australia). Each probe was calibrated in the field at the end of the study by measuring the probe output (mV) at varying soil water contents, and then immediately collecting a soil sample to determine gravimetric water content and bulk density after drying at 105°C.

Grain yield

In 2012 and 2014, grain yield was measured inside the chamber areas at maturity (29 November 2012, 4 November 2014). The above ground biomass and grain yield was measured by collecting the material that would pass through a harvester (plant shoot >150 mm above the ground), with the remaining plant material retained. All plant material was oven dried at 60°C for at least one week before recording the dry mass, and then threshed to collect (and weigh) the grain. Once the chamber sampling was completed, the grain from the remainder of the plot was removed using a conventional harvester.

In 2013, plant emergence was highly variable both within and outside the chamber bases due to variable seeding depth and poor rainfall. Plant material was collected using a similar approach as described above, however grain yield data was found to be highly variable within treatments. Consequently in 2013 grain yield was calculated using data collected from the N response plots at the same study site (see below for details).

Soil and climatic measurements

Micrometeorological data was collected throughout the study using an onsite weather station. Rainfall was measured using a 204 mm diameter automated tipping rain gauge (TB3, Hydrological Services, Warwick Farm, NSW, Australia) with a resolution of 0.2 mm, air temperature was measured at 1.2 m height using a platinum resistance element (PT100 RTD, Vaisala, Finland), while soil temperature was measured at 100 mm depth using a sealed platinum resistance element (PT100 RTD, MTL Engineering Australia, Canning Vale, Western Australia, Australia). All micrometeorological data was collected and stored automatically by a data logger (DataTaker 50, Data Electronics, Scoresby, Victoria, Australia). Air temperature within a single chamber per set of four chambers was recorded every minute during chamber closure using a temperature probe (Pt100, IMKO, Ettlingen Germany).

Statistics and data analysis

Hourly N_2O ($\mu\text{g N}_2\text{O-N m}^{-2} \text{h}^{-1}$) and CH_4 ($\mu\text{g CH}_4\text{-C m}^{-2} \text{h}^{-1}$) fluxes were calculated from the slope of the linear increase in N_2O or CH_4 concentration during the chamber lid closure period, and corrected for chamber air temperature, air pressure and the ratio of cover volume to surface area as described by Barton et al. (2008). Flux rates were converted to zero if the

regression coefficient (r^2) was < 0.80 . Daily losses for each plot were calculated by averaging hourly losses for that day. Annual fluxes for each plot were calculated by integrating hourly losses over time.

The emission factor for the application of N fertiliser to the soil was calculated for each OM treatment using:

$$EF = \frac{[N_2O-N \text{ total (+N)}] - [N_2O-N \text{ total (0N)}]}{\text{Total N fertiliser applied}}$$

where, EF is the emission factor (N_2O -N emitted as % of fertiliser-N applied), N_2O -N total (+N) and N_2O -N total (0N) are the mean cumulative N_2O emissions ($kg\ N\ ha^{-1}\ yr^{-1}$) from the plus N and no N fertiliser plots, respectively.

All data were statistically analysed using Genstat for Windows, 14th edition (<http://www.vsni.co.uk/>). A general linear model was used to determine whether OM addition or fertiliser application affected measured annual N_2O and CH_4 emissions. Post-hoc pair-wise comparisons of means were made using least significant difference (LSD) at the 5% level.

Assessing the effect of SOC on N fertiliser requirements

Another key question investigated by the research project was: Does increasing SOC alter N fertiliser requirements? The following section outlines the methods and activities used to address this question.

Experimental design and approach

In 2013 and 2014, grain yield response to a range of N fertiliser applications (0 – $100\ kg\ N\ ha^{-1}$) were determined on replicated (three) field blocks of contrasting SOC (i.e., OM+tillage, Tillage) at the Long Term Research Site at Buntine (described above). Blocks were planted to barley (*Hordeum vulgare* cv Hindmarsh) on 5 June 2013, and to oats (*Avena sativa* cv Brusher) on 6 May 2014. In 2013, plots received $40\ kg\ ha^{-1}$ of triple superphosphate inserted to a soil depth of 30 mm at planting, whereas in 2014 no fertiliser was applied at planting. The blocks were further divided into 5 plots ($40\ m^2$), with each randomly allocated a different N fertiliser rate (0, 25, 50, 75 or $100\ kg\ N\ ha^{-1}$; top-dressed as urea) approximately four weeks after seeding (3 July 2013, 3 June 2014). Plots were relocated each year.

Findings from Buntine were compared with reported grain yield response to N fertiliser applications at two additional study sites (planted to barley) per year for three years in the Western Australian grain belt. Field sites were planted to barley at Cunderdin ($31^\circ\ 38'\ S$, $117^\circ\ 15'\ E$; 2012, 2013), Walebing ($30^\circ\ 37'\ S$, $116^\circ\ 17'\ E$; 2012), Wongan Hills ($30.90^\circ\ S$, $116.72^\circ\ E$; 2014) and York ($31^\circ\ 86'\ S$, $116^\circ\ 80'\ E$; 2013, 2014). At each location, the randomised block design included two barley varieties (*Hordeum vulgare* cv Baudin or Buloke) by five N fertiliser rates (0, 25, 50, 75, $100\ kg\ N\ ha^{-1}$) by three replicates. Sites were seeded on either the 9 June 2012 (Cunderdin), 18 June 2012 (Walebing), 15 May 2013 (York), 29 May 2013 (Cunderdin), 15 May 2014 (York) or 16 May 2014 (Wongan Hills); with all plots ($10.5\ m^2$) receiving $120\ kg\ ha^{-1}$ of 'Super CZM' (contains no N) inserted to a soil depth of 30 mm at planting. The N fertiliser (urea) treatments were surface applied by hand approximately four weeks after seeding (9 July 2012, Cunderdin; 16 July 2012,

Walebing; 12 June 2013, York; 26 June 2013, Cunderdin; 11 June 2014, York; 16 June 2014, Wongan Hills). Grain was harvested (November each year) using an experimental harvester.

Soil, environment and site characterisation

The soil at each study site was characterised using the Australian Soil Classification system. The surface soil (0–10cm) was also analysed for properties commonly measured by growers for determining crop fertiliser requirements prior to seeding each year, with analyses conducted by a typical soil testing laboratory (CSBP Limited). Soil mineral N (increments to 600 mm depth) were measured prior to seeding, and four weeks after seeding (immediately prior to N fertiliser application). In 2014, soil sampling at one site for mineral N analysis was limited to 300 mm as a hard-pan prevented staff from auguring beyond this depth. Daily rainfall during the growing season was measured either using data collected by either an onsite automated rain gauge or the closest Bureau of Meteorology weather station.

Plant emergence, plant N uptake, grain yield and quality

Plant emergence was measured four weeks after planting by recording the number of seedlings along transects (3–4 m transects per plot, depending on the year) in each plot. In 2013 and 2014, above-ground plant samples were collected at anthesis (2–4 m transects per plot, depending on the site) to determine shoot dry matter biomass, grain head number, and plant N content. The plant shoots were dried and ground before being analysed for total N using a CNS analyser (Elementar Analysensysteme GmbH, Vario Macro, Hamau, Germany). Crop yield and quality were measured at plant maturity. Plots were harvested using an experimental harvester that enabled grain weight to be measured. A subsample of the harvested grain was further analysed for moisture content, protein and other grain quality parameters.

Statistics and data analysis

All data were statistically analysed using Genstat for Windows, 14th edition (<http://www.vsni.co.uk/>). A general linear model was used to determine whether barley variety, fertiliser application or OM addition (Buntine study site only) affected grain yield and quality. Post-hoc pair-wise comparisons of means were made using LSD (significance level of 5%). In 2013, data for each barley variety at the York study site was pooled (by N fertiliser rate) due to a site establishment error.

Results

Assessing the effect of SOC on N₂O emissions

Rainfall

The Buntine study site received 287 mm (164 mm during the growing season) in 2012 (Figure 1c), which was less than the average annual rainfall (338 mm) for the area and partly attributed to low rainfall in July and August. In 2013 and 2014, the site received 269 mm (189 mm during growing season) and 234 mm (185 mm during growing season), respectively (Figure 1c).

Nitrous oxide emissions

Hourly N₂O fluxes ranged from -99 to 156 µg N₂O-N m⁻² h⁻¹ during the study. Hourly emissions tended to be greater from the OM+tillage treatment than the Tillage treatment following summer and autumn rainfall and the application of N fertiliser (Figure 1a). Cumulative N₂O emissions were greater from the OM+tillage than the Tillage treatments ($P < 0.05$) after 2.5 years, while applying N fertiliser only increased emissions from the OM+tillage treatment (Table 2). Consequently, total N₂O losses after 2.5 years ranged from 7 g N₂O-N ha⁻¹ (Tillage, no N fertiliser) to 427 g N₂O-N ha⁻¹ (OM+tillage, plus N fertiliser) (Table 2; $P < 0.05$).

The proportion of N fertiliser emitted as N₂O for each one year study period, and after correction for the 'background' emission (no N fertiliser applied), ranged from 0.08 to 0.12 % for the OM+tillage treatment (Table 2). An emission factor for the Tillage treatment was not calculated as cumulative N₂O emission did not differ between the plus and no fertiliser treatment for any of the study periods ($P > 0.05$).

Table 2. Cumulative N₂O emissions and emission factors for each treatment. Values represent means of three replicates. Values followed by the same letter in the same row are not significantly different ($P < 0.05$).

Study Period [†]	Cumulative N ₂ O emission (g N ₂ O-N ha ⁻¹)				Emission Factor (%)	
	OM+tillage (Plus N)	OM+tillage (No N)	Tillage (Plus N)	Tillage (No N)	OM+tillage	Tillage
Year 1	138 ^a	56 ^b	22 ^b	14 ^b	0.08	NA
Year 2	271 ^a	146 ^b	19 ^c	0 ^c	0.12	NA
Year 3	18 ^a	-8 ^{ab}	-1 ^{ab}	-7 ^{ab}	ND	ND
All years	427 ^a	194 ^b	41 ^c	7 ^c	ND	ND

[†]Year 1, 7 June 2012–7 June 2013; Year 2, 7 June 2013–7 June 2014; Year 3, 7 June 2014–5 December 2014; NA, not applicable, as N₂O emission did not differ between the plus and no fertiliser treatment; ND, not determined, as hourly N₂O fluxes not measured for 12 months.

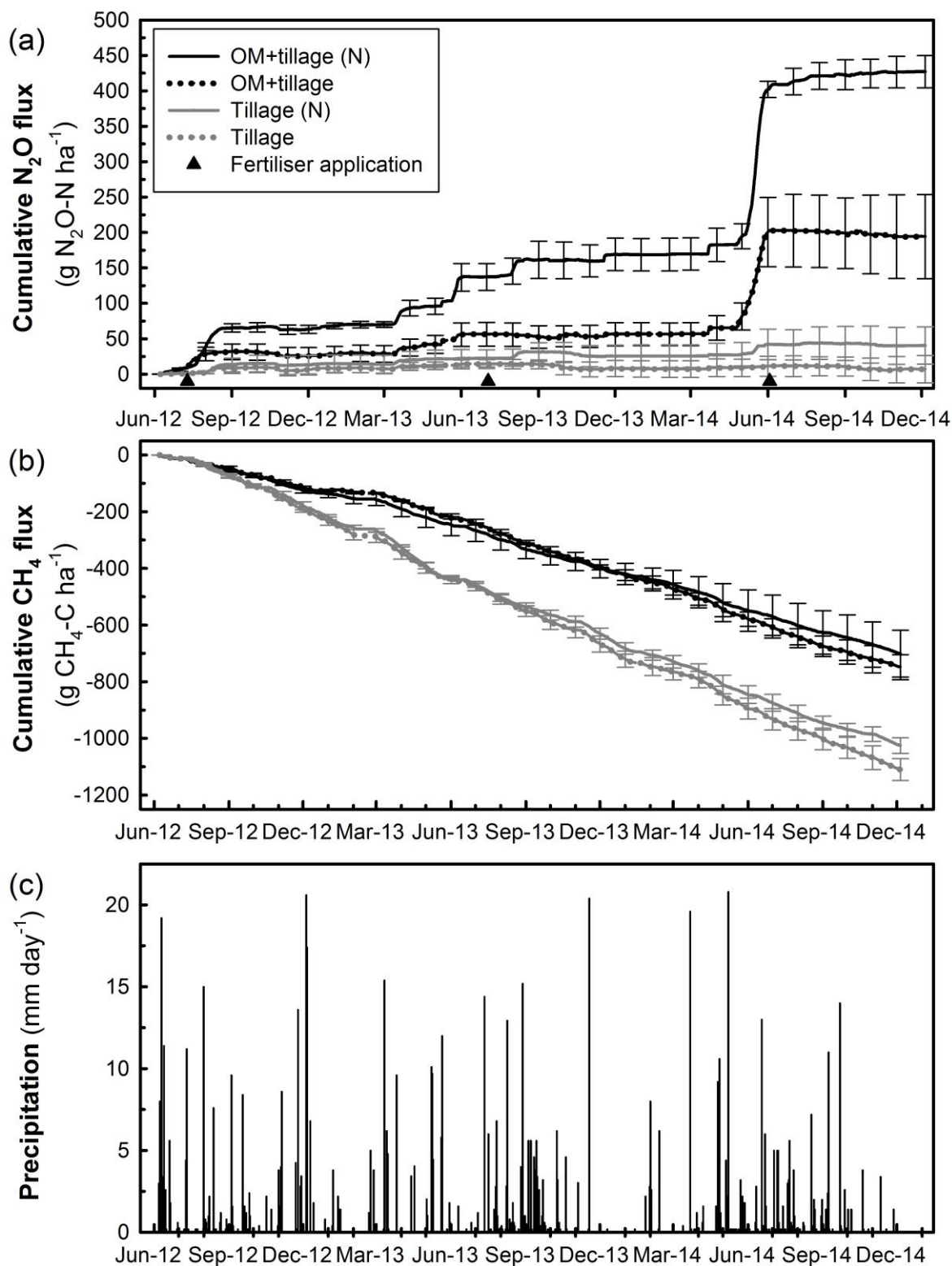


Figure 1. Cumulative N_2O fluxes (a), cumulative CH_4 fluxes (b) and daily precipitation (c) with time at Buntine, Western Australia (7 June 2012 – 5 December 2014). Cumulative N_2O and CH_4 fluxes represent means (\pm standard errors) of three replicates. The triangles indicate the timing of N fertiliser application. The legend in (a) also applies to (b).

Methane emissions

Hourly CH₄ fluxes ranged from -211 to 170 µg CH₄-C m⁻² h⁻¹ during the study. Methane uptake was measured in all treatments each year, but to a greater extent in the Tillage than the OM+tillage treatments ($P<0.05$), and was unaffected by the application of N fertiliser ($P>0.05$; Figure 1b). Consequently, total CH₄ uptake after 2.5 years was ranked: Tillage, plus N fertiliser (-1025 g CH₄-C) = Tillage, no N fertiliser (-1110 g CH₄-C ha⁻¹; Figure 1b) > OM+tillage, no N fertiliser (-748 g CH₄-C ha⁻¹) = OM+tillage, plus N fertiliser (-701 g CH₄-C ha⁻¹) (Table 3). Furthermore, CH₄ uptake offset N₂O emissions from the Tillage treatments in the first two years of the study (Table 4).

Table 3. Cumulative CH₄ emissions for each treatment. Values represent means of three replicates. Values followed by the same letter in the same row are not significantly different ($P<0.05$).

Study Period [†]	Cumulative CH ₄ emission (g CH ₄ -C ha ⁻¹)			
	OM+tillage (Plus N)	OM+tillage (No N)	Tillage (Plus N)	Tillage (No N)
Year 1	-251 ^a	-226 ^a	-438 ^b	-444 ^b
Year 2	-303 ^a	-358 ^{ab}	-411 ^{bc}	-454 ^c
Year 3	-148 ^a	-165 ^a	-176 ^{ab}	-212 ^b
All years	-701 ^a	749 ^a	-1025 ^b	-1110 ^b

[†]Year 1, 7 June 2012–7 June 2013; Year 2, 7 June 2013–7 June 2014; Year 3, 7 June 2014–5 December 2014.

Table 4. Nitrous oxide and CH₄ fluxes expressed as CO₂-equivalents for each treatment after two years of measurements[†]. Values represent means of three replicates. Values followed by the same letter in the same column are not significantly different ($P<0.05$).

OM treatment	N treatment	CO ₂ -equivalent (kg CO ₂ ha ⁻¹) [‡]		
		N ₂ O	CH ₄	Total
OM+tillage	Plus	72.0 (7.4) ^a	-25.1 (3.4) ^a	47.9 (9.7) ^a
OM+tillage	No	22.4 (9.9) ^b	-26.5 (1.2) ^a	-4.0 (10.8) ^b
Tillage	Plus	9.9 (7.2) ^b	-38.5 (1.4) ^b	-28.6 (6.0) ^{bc}
Tillage	No	3.2 (5.1) ^b	-40.7 (1.7) ^b	-37.5 (6.8) ^c

[†]7 June 2012–7 June 2014. CO₂-equivalents are calculated using the first two years of data (rather than 2.5 years) due to intra-annual variability in daily N₂O fluxes.

[‡]CO₂-equivalents calculated using a global warming potential of 298 for N₂O, and 34 for CH₄ (Myhre et al., 2013).

Volumetric water content (VWC), mineral N and dissolved organic C

Soil VWC measured in the surface 100 mm varied on a subdaily basis in response to rainfall, but in a similar way for all treatments (compare Figures 1c and 2d). Although values ranged from <2 to 36% (<5 to 84% WFPS) during the study, the median soil VWC was 2.4%.

The amount of inorganic N (NO_3^- plus NH_4^+) in the surface soil (0–100 mm) during study varied in response to the application of N fertiliser or to summer rainfall (Figure 2a, b). Soil NH_4^+ changed mainly in response to N fertiliser applications, and in the surface 100 mm ranged from <1 to 83 kg N ha⁻¹ for treatments that received N fertiliser, and from <1 to 8 kg N ha⁻¹ for treatments that did not receive fertiliser (Figure 2b). The amount of NO_3^- in the surface 100 mm ranged from <1 to 62 kg N ha⁻¹ and increased in response to both N fertiliser applications and summer rainfall events. Soil NO_3^- tended to be greater in the OM+tillage than the Tillage treatments irrespective of the application of N fertiliser (Figure 2a).

Dissolved organic C in the surface soil (0–100 mm) ranged from 28 to 227 $\mu\text{g C g}^{-1}$ dry soil during the study and varied in response to OM treatment and summer rainfall (compare Figures 1c and 2c). Average dissolved organic C tended to be greater for the OM+tillage than the Tillage treatment: values ranged from 51 to 227 $\mu\text{g C g}^{-1}$ dry soil for the OM+tillage treatment (combined N fertiliser rate), and 28 to 158 $\mu\text{g C g}^{-1}$ dry soil for Tillage treatment (combined N fertiliser rate).

Grain yield

Grain yield at the Buntine study site averaged 1.31 t ha⁻¹ (canola) in 2012, 3.12 t ha⁻¹ (barley) in 2013, and 0.21 t ha⁻¹ (oats) in 2014. In 2012 and 2013, yield was greater for the OM+tillage soil than the Tillage soil, and unaffected by the application of N fertiliser in both years (Table 5). By contrast, in 2014, yield was not affected by OM treatment and was decreased by the addition of N fertiliser (Table 2). The suppression of the grain yield by N fertiliser addition was consistent with other yield measurements at the study site in 2014 (Figure 4).

Table 5. Grain yield for each growing season. Values represent means (standard errors) of three replicates. Values in the same column followed by the same letter are not significantly different ($P < 0.05$).

OM Treatment	N fertiliser rate (kg N/ha)	2012 Canola Yield [†] (t ha ⁻¹)	2013 Barley Yield [‡] (t ha ⁻¹)	2014 Oat Yield [†] (t ha ⁻¹)
OM + tillage	100	1.51 (0.15) ^a	3.56 (0.31) ^a	0.13 (0.00) ^a
OM + tillage	0	1.55 (0.02) ^a	3.39 (0.03) ^a	0.29 (0.05) ^b
Tillage	100	1.22 (0.13) ^b	2.87 (0.23) ^b	0.15 (0.02) ^a
Tillage	0	0.95 (0.03) ^b	2.66 (0.05) ^b	0.26 (0.01) ^b

[†]Yield calculated using grain collected from chambers. [‡]Yield calculated using grain collected from plots used for N fertiliser response study due to non-uniform emergence in areas used to measure N₂O emissions.

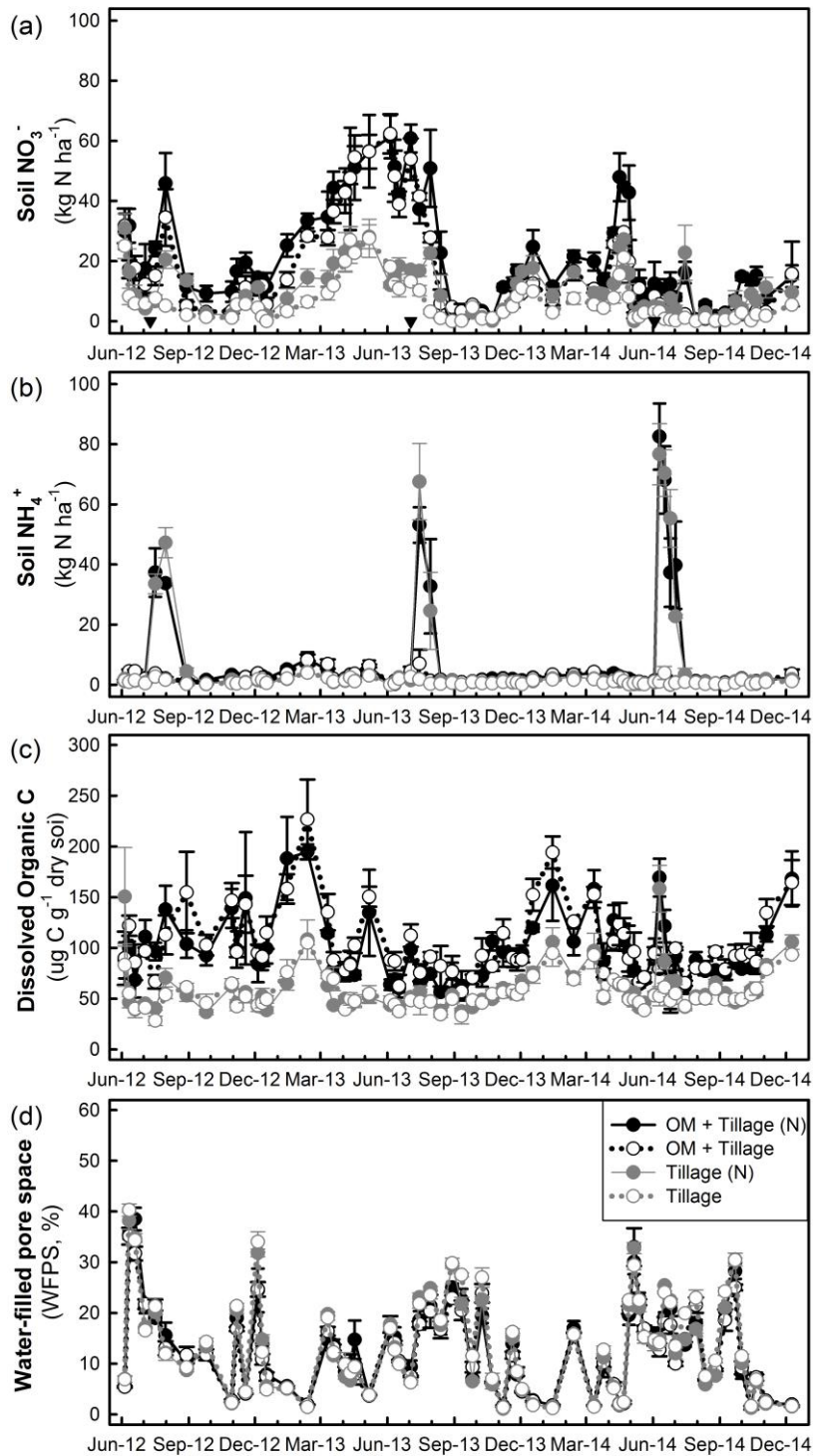


Figure 2. Soil nitrate (NO_3^- , a) concentration, ammonium (NH_4^+ , b) concentration, dissolved organic C (DOC, c), and volumetric water content (VWC, d) in the surface 100 mm of soil with time (7 June 2012–9 December 2014) for each soil organic matter (OM) and nitrogen (N) fertiliser treatment at Buntine, Western Australia. Volumetric water content data for OM treatment averaged across N fertiliser rate. Values represent means (\pm standard errors) of three replicates, except for VWC data where means are of up to four replicates (errors bar excluded to improve clarity). The triangles indicate the timing of N fertiliser application. The legend in (a) also applies to (b) and (c).

Rainfall and soil characteristics

The Buntine study site received 269 mm (189 mm during growing season) in 2013, and 234 mm (185 mm during growing season) in 2014. The distribution of monthly rainfall varied significantly between 2013 and 2014 (Figure 3). For example in 2013, the region experienced a particularly dry winter followed by a ‘wet’ spring. In 2014 there was good opening rains, however this was followed by below average winter rainfall. Incorporating additional OM into the soil since 2003 increased a number of soil nutrients in the surface 100 mm, particularly P and K (Table 6).

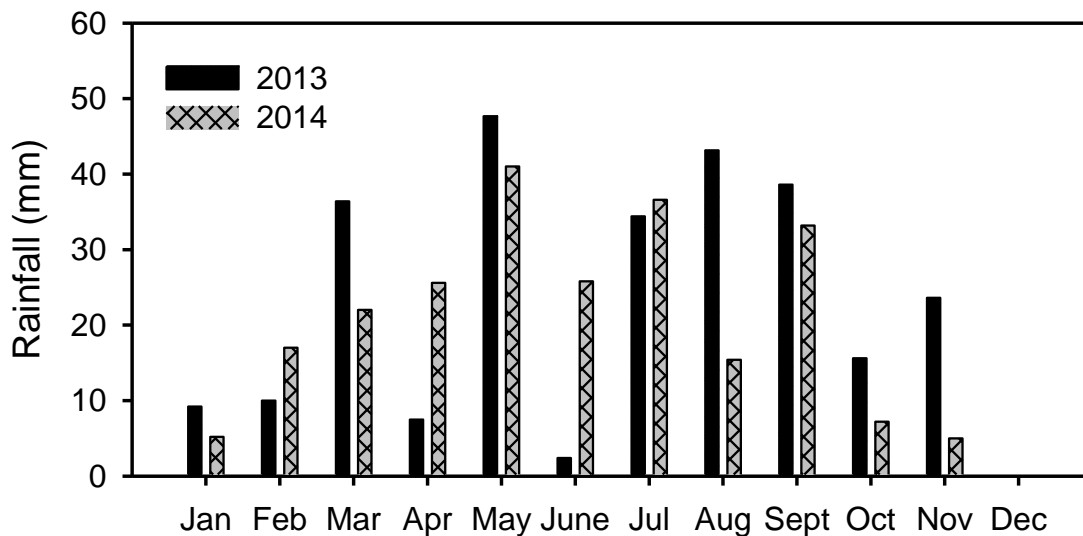


Figure 3. Distribution of annual rainfall at the Buntine site in 2013 and 2014.

Table 6. Chemical analysis (surface 100 mm)[†] and soil classification of Buntine N response study sites in the Western Australian grain belt. Values are means (and standard errors) of three field replicates.

Soil property	2013		2014	
	OM+ tillage	Tillage	OM+ tillage	Tillage
Ammonium (mg NH ₄ ⁺ -N kg ⁻¹)	5.3 (0.3)	3.7 (0.3)	6.7 (0.9)	3.0 (0.0)
Nitrate (mg NO ₃ ⁻ -N kg ⁻¹)	19 (2.3)	13 (3.7)	22 (0.6)	16 (0.9)
Phosphorus (mg P kg ⁻¹)	62 (6.3)	32 (1.4)	65 (2.8)	35 (4.3)
Potassium (mg K kg ⁻¹)	286 (21)	98 (8.7)	292 (9.1)	98 (16)
Sulphur (mg S kg ⁻¹)	49 (11)	30 (8.8)	34 (5.6)	15 (3.7)
Organic C (%)	1.8 (0.2)	1.2 (0.02)	1.8 (0.3)	1.0 (0.06)
Electrical conductivity (dS m ⁻¹)	0.20 (0.02)	0.13 (0.02)	0.22 (0.02)	0.10 (0.0)
pH (0.1M CaCl ₂)	6.6 (0.09)	6.5 (0.12)	6.5 (0.2)	6.5 (0.2)
pH (H ₂ O)	7.2 (0.09)	7.0 (0.09)	7.2 (0.0)	7.0 (0.2)
Australian Soil Classification (Isbell, 2002)	Basic Regolithic Yellow-Orthic Tenosol			

[†]Chemical analysis completed using a typical soil test employed by growers in the Western Australian grain belt.

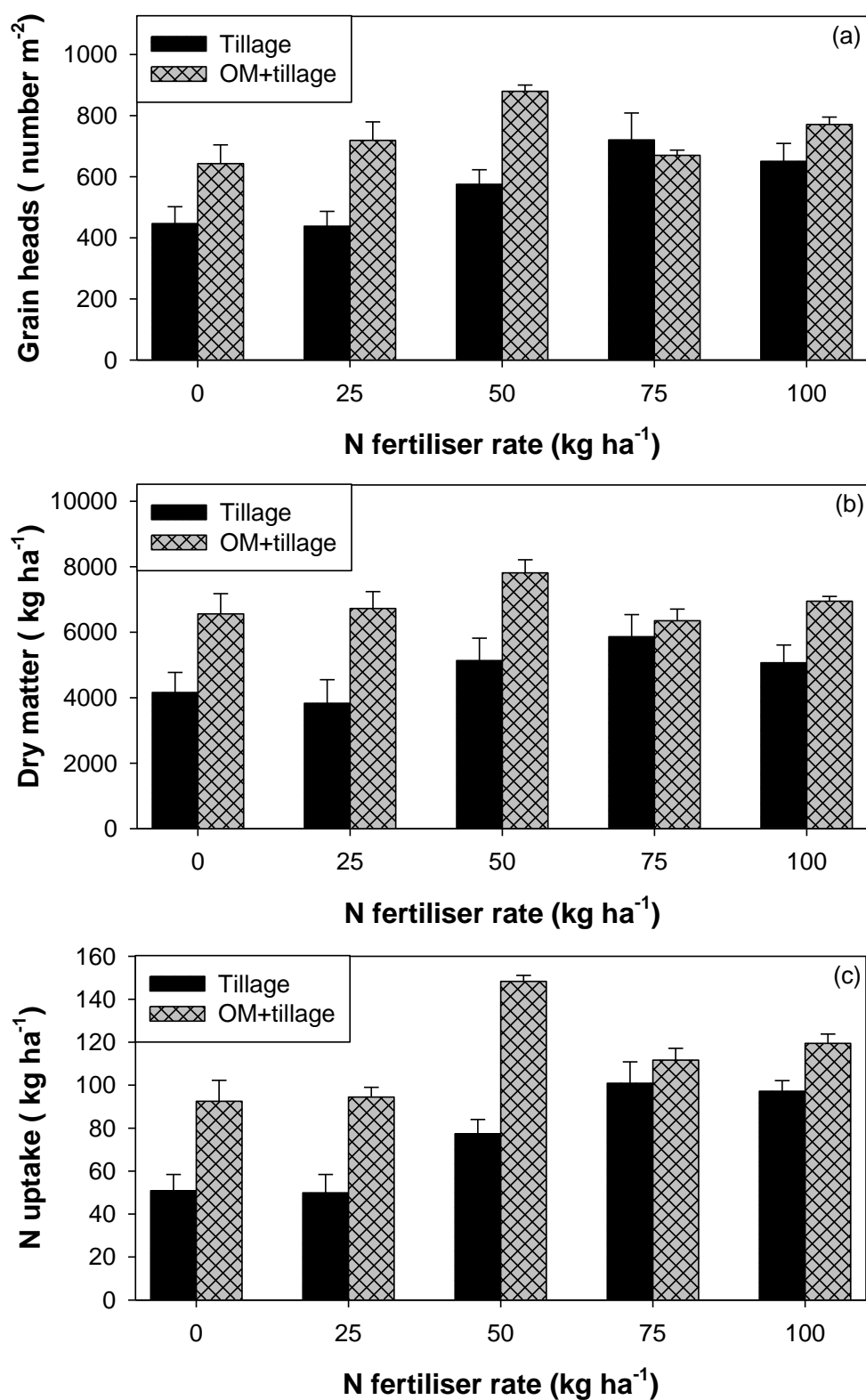


Figure 4. Barley grain head numbers (a) and dry matter production (b) and N content of aboveground biomass (N uptake; c) in response to varying N fertiliser application rates at anthesis in 2013 for the Tillage and OM+tillage treatments at Buntine, Western Australia. Values represent means (\pm standard errors) of three replicates.

Grain yield and grain quality

Progressively adding OM to the soil during the past 10 years increased grain yield in 2013 and 2014 ($P < 0.05$; Figure 5). Applying N fertiliser did not affect yield in 2013, but did cause a decline in grain yield in 2014. In 2013, barley grain yield was 2.8 t ha^{-1} for the Tillage treatment (averaged across N fertiliser rates) and 3.4 t ha^{-1} for the OM+tillage treatment (averaged across N fertiliser rates). In 2014, oat grain yield was 0.28 t ha^{-1} for the Tillage treatment (averaged across N fertiliser rates) and 0.46 t ha^{-1} for the OM+tillage treatment (averaged across N fertiliser rates).

In 2013, barley grown in OM+tillage treatment met all the quality standards required for malting barley without applying N fertiliser (Figure 6). Indeed, applying more than 25 kg N ha^{-1} to the OM+tillage treatment would have risked the barley being classed as ‘animal feed’ due to the high protein content. The barley grown in the Tillage treatment did not meet the malting barley standards for any of the N fertiliser rates due to high screenings and/or high protein contents (Figure 6).

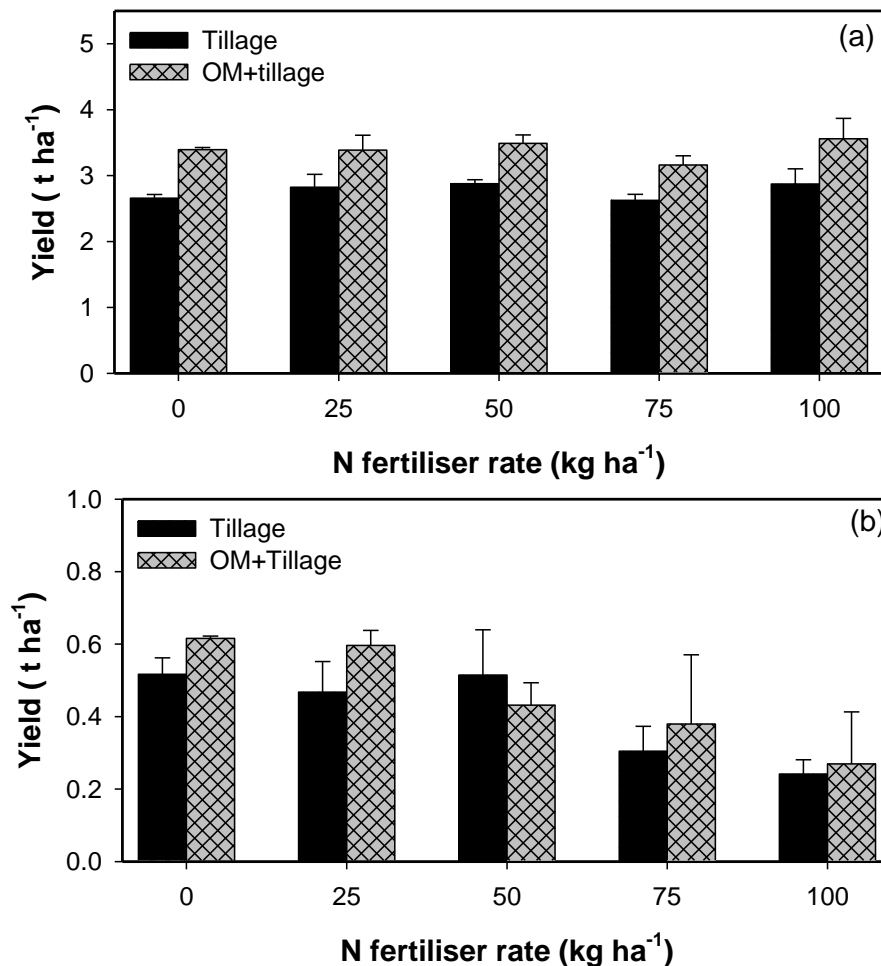


Figure 5. Grain yield response to varying N fertiliser application rates for the Tillage and OM+tillage treatments at Buntine in 2013 when sown to barley (a), and in 2014 when sown to oats (b). Yields represent means (\pm standard errors) of three replicates.

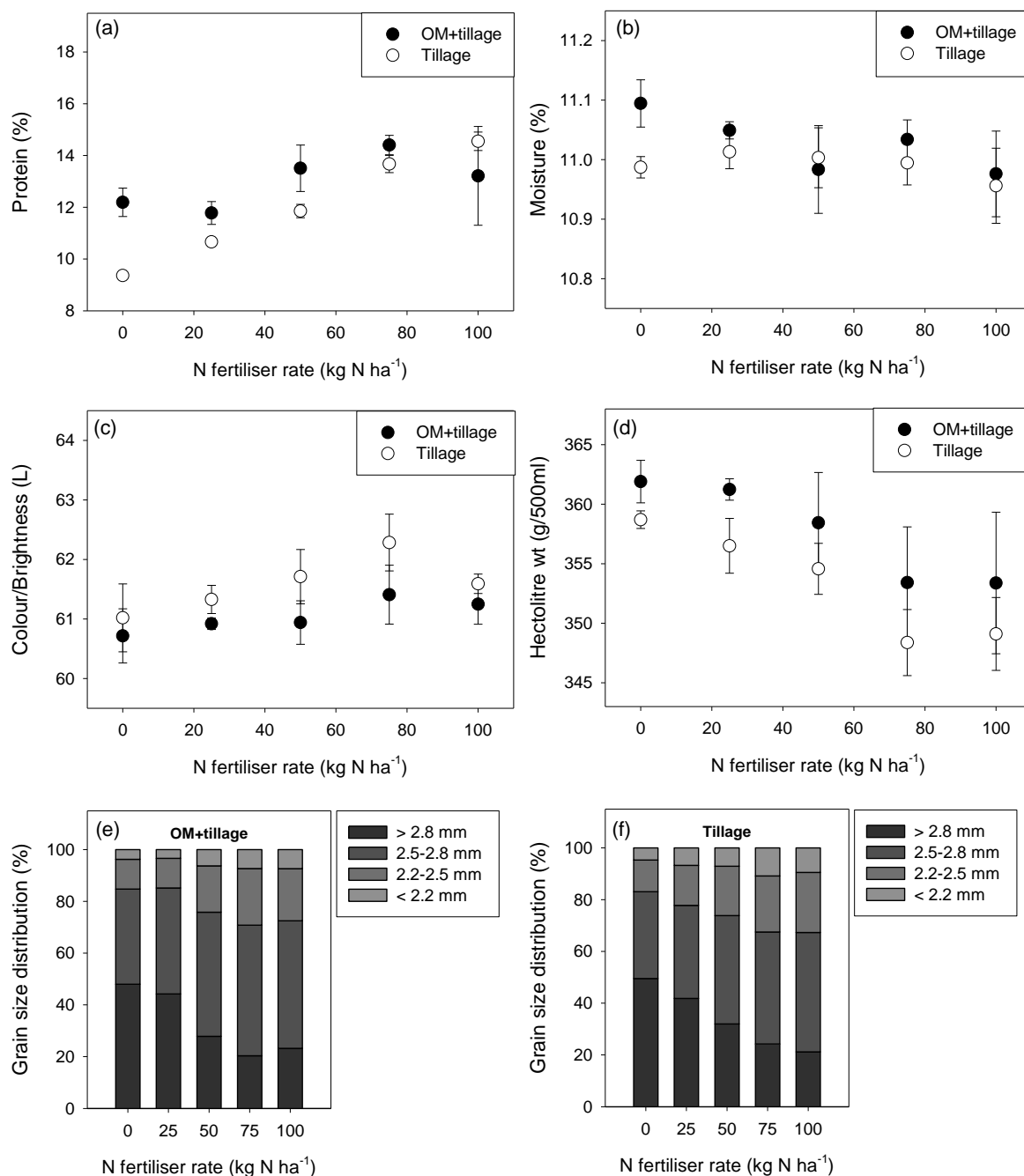


Figure 6. Grain quality parameters for barley at Buntine in 2013. Quality standards for malting barley: Protein, 9.5–12.5%; Moisture, $\leq 12.5\%$; Colour (L) ≥ 56 ; Hectolitre weight ≥ 320 g/500mL; Grain size, contains $\leq 20\%$ grain that is < 2.5 mm. Quality standards are based on CBH 2013/14 Malting Barley Receival Standards. Values represent means of three replicates.

Assessing the effect of SOC on N fertiliser requirements: WA grain belt

The following section reports findings from research sites in the Western Australian grain belt that were planted to barley in the 2012, 2013 and 2014 growing seasons.

Rainfall

In 2012, the annual and growing season (May–October) rainfall varied considerably between the two study sites (Cunderdin and Walebing; Figure 7a). The annual rainfall for Cunderdin was 228 mm (137 mm during the growing season), while the annual rainfall for Walebing was 284 mm (206 mm during the growing season).

In 2013, both study sites (Cunderdin and York; Figure 7b) received good opening rains in May, which was followed by a particularly dry June (<5mm). The annual rainfall for Cunderdin was 374 mm (271 mm during the growing season), while the annual rainfall for York was 353 mm (274 mm during the growing season); rain at both sites was above average.

In 2014, the annual rainfall for Wongan Hills was 388 mm (301 mm during the growing season), while the annual rainfall for York was 409 mm (394 mm during the growing season) (Figure 7c). Annual rainfall was above average for both Wongan Hills and York.

Soil characteristics

The study sites have provided contrasting soil types and properties throughout the three year study (Table 8). Surface soils have ranged from sand (Wongan Hills, 2014), to clay loams (Cunderdin, 2012; Walebing, 2012) and loamy clays (York, 2013).

Soil mineral N contents

The amount of mineral N (NO_3^- plus NH_4^+) in the soil profile (0–600mm) prior to seeding varied at least two-fold between study sites each year (Table 9). The change in soil mineral N following seeding, and immediately prior to applying N fertiliser (generally four weeks after seeding), also varied between study sites each year (Table 9). For example in 2012, mineral N increased from 124 to 206 kg N ha⁻¹ in the surface 600 mm at Cunderdin between seeding and prior to N fertiliser application, whereas over the same period mineral N declined from 61 to 51 kg N ha⁻¹ at Walebing. Similarly in 2013, mineral N increased from 54 to 88 kg N ha⁻¹ in the surface 600 mm at Cunderdin, but declined from 112 to 69 kg N ha⁻¹ at York. In 2014, mineral N in the soil profile was considerably less than previous years, which we attribute to low summer rainfall in 2014 limiting soil N mineralisation.

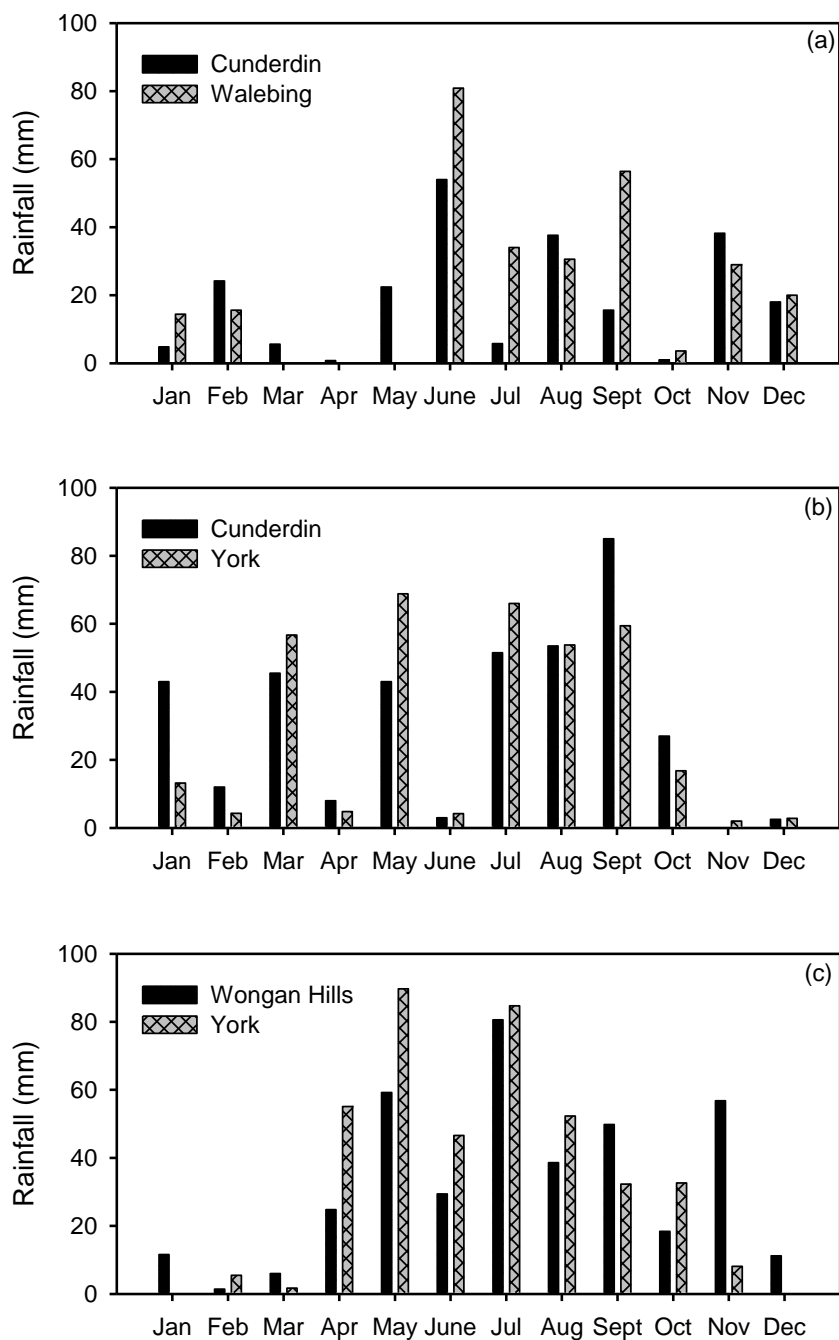


Figure 7. Monthly rainfall distribution study sites at Cunderdin and Walebing in 2012 (a), Cunderdin and York in 2013 (b), and Wongan Hills and York in 2014 (c).

Table 8a. Chemical analysis (surface 100 mm)[†] and soil classification of N response study sites in the Western Australian grain belt in 2012. Values are means (and standard errors) of three field replicates (five bulked samples per field replicate).

Soil parameter	Cunderdin	Walebing
Ammonium (mg NH ₄ ⁺ -N kg ⁻¹)	10 (3.5)	2.5 (0.4)
Nitrate (mg NO ₃ ⁻ -N kg ⁻¹)	37 (4.0)	36 (4.4)
Phosphorus (mg P kg ⁻¹)	35 (3.6)	53 (2.7)
Potassium (mg K kg ⁻¹)	670 (12)	218 (30)
Sulphur (mg S kg ⁻¹)	19 (2.0)	23 (0.7)
Organic C (%)	1.26 (0.1)	1.52 (0.01)
Electrical conductivity (dS m ⁻¹)	0.14 (0.006)	0.17 (0.00)
pH (0.1M CaCl ₂)	5.60 (0.3)	5.63 (0.2)
pH (H ₂ O)	6.37 (0.3)	6.40 (0.2)
Australian Soil Classification	Red (AA) Hypercalcic (CQ) Sodosol	Brown (AB) Dermosol

[†]Chemical analysis completed using a typical soil test employed by growers in the region.

Table 8b. Chemical analysis (surface 100 mm)[†] and soil classification of N response study sites in the Western Australian grain belt in 2013. Values are means (and standard errors) of three field replicates (five bulked samples per field replicate).

Soil parameter	Cunderdin	York
Ammonium (mg NH ₄ ⁺ -N kg ⁻¹)	<1 (0.0)	6.0 (0.0)
Nitrate (mg NO ₃ ⁻ -N kg ⁻¹)	33 (0.6)	43 (0.3)
Phosphorus (mg P kg ⁻¹)	25 (0.9)	60 (0.6)
Potassium (mg K kg ⁻¹)	113 (9)	376 (2.0)
Sulphur (mg S kg ⁻¹)	20 (0.2)	29 (0.4)
Organic C (%)	1.25 (0.3)	1.89 (0.01)
Electrical conductivity (dS m ⁻¹)	0.14 (0.0)	0.20 (0.01)
pH (0.1M CaCl ₂)	5.10 (0.06)	6.20 (0.0)
pH (H ₂ O)	5.70 (0.06)	6.63 (0.03)
Australian Soil Classification	Brown (AB) Kurosol	Brown (AB) Dermosol

[†]Chemical analysis completed using a typical soil test employed by growers in the region.

Table 8c. Chemical analysis (surface 100 mm)[†] and soil classification of N response study sites in the Western Australian grain belt in 2014. Values are means (and standard errors) of three field replicates (five bulked samples per field replicate).

Soil parameter	Wongan Hills	York
Ammonium (mg NH ₄ ⁺ -N kg ⁻¹)	5.0 (0.0)	7.3 (0.3)
Nitrate (mg NO ₃ ⁻ -N kg ⁻¹)	6.3 (0.9)	6.3 (0.3)
Phosphorus (mg P kg ⁻¹)	34 (1.2)	54 (1.9)
Potassium (mg K kg ⁻¹)	203 (23)	208 (30)
Sulphur (mg S kg ⁻¹)	55 (2.7)	168 (16)
Organic C (%)	1.2 (0.06)	2.2 (0.02)
Electrical conductivity (dS m ⁻¹)	0.16 (0.01)	0.34 (0.05)
pH (0.1M CaCl ₂)	5.0 (0.09)	5.3 (0.13)
pH (H ₂ O)	5.7 (0.1)	5.7 (0.1)
Australian Soil Classification	Yellow Kandosol	Brown Chromosol

[†]Chemical analysis completed using a typical soil test employed by growers in the region.

Table 9. Soil mineral N contents (kg N ha⁻¹) with soil depth. Values represent means (and standard errors) of twelve field replicates.

Soil depth (mm)	2012		2013		2014	
	Cunderdin	Walebing	Cunderdin	York	Wongan Hills	York
	<i>Seeding</i> [†]					
0–100	50 (8.1)	30 (3.4)	33 (5.3)	56 (5.5)	15 (1.5)	22 (1.6)
100–200	36 (4.4)	15 (1.6)	13 (1.1)	23 (5.8)	8.2 (1.5)	11 (1.1)
200–400	12 (0.5)	10 (1.6)	4.7 (0.8)	7.7 (1.8)	3.6 [§] (0.6)	8.3 (0.5)
400–600	7.2 (0.7)	6.2 (1.4)	0.7 (0.2)	2.5 (0.4)	ND*	4.4 (0.4)
	<i>Four weeks after seeding</i> [‡]					
0–100	67 (15)	19 (2.5)	40 (14)	25 (2.6)	6.4 (0.8)	8.9 (1.0)
100–200	67 (8.5)	19 (2.7)	25 (4.4)	24 (1.7)	7.5 (0.7)	6.7 (1.1)
200–400	24 (2.3)	8.9 (1.2)	12 (4.3)	13 (1.3)	5.2 [§] (0.4)	7.2 (0.6)
400–600	11 (0.7)	4.3 (1.1)	11 (5.8)	6.7 (0.5)	ND*	7.9 (0.5)

[†]Soil samples collected on the 11 June 2012 (Cunderdin), 12 June 2012 (Walebing), 20 May 2013 (York), 29 May 2013 (Cunderdin), 19 May 2015 (Wongan Hills), and 21 May 2015 (York). [‡]Soil samples collected on the 9 July 2012 (Cunderdin), 16 July 2012 (Walebing), 3 June 2013 (York), and 29 June 2013 (Cunderdin), 16 June 2014 (Wongan Hills), and 13 June 2014 (York). [§] Presence of hardpan limited sampling to 200-300mm depth. *ND, not determined.

Plant establishment, grain yield and quality

Plant emergence four weeks after planting (and prior to applying N fertiliser treatments; averaged across variety) averaged 177 plants m⁻² at Cunderdin (2012), 156 plants m⁻² at Walebing (2012), 153 plants m⁻² at Cunderdin (2013), 180 plants m⁻² at York (2013), 172 plants m⁻² at Wongan Hills (2014) and 170 plants m⁻² at York (2014).

Barley grain yield varied greatly between the study sites, and between study years. In 2012 at Cunderdin, the grain yield averaged 1.52 t ha⁻¹ and varied depending upon variety ($P < 0.05$) and N fertiliser rate ($P < 0.05$; Figure 8). The ‘Baudin’ variety averaged 1.33 t ha⁻¹ and did not respond to N fertiliser applications. Buloke averaged 1.70 t ha⁻¹ and yield declined with increasing N fertiliser rate. At Walebing in 2012, grain yield averaged 5.0 t ha⁻¹ and did not vary with variety ($P > 0.05$), and instead only varied in response to N fertiliser rate ($P < 0.05$; Figure 8). In 2013, grain yield averaged 5.10 t ha⁻¹ at Cunderdin and 5.76 t ha⁻¹ at York (averaged across variety), with no response to N fertiliser rate at either site (Figure 9). In 2014, grain yield averaged 3.12 t ha⁻¹ at Wongan Hills and did not vary with variety or N fertiliser rate ($P > 0.05$; Figure 9). By contrast, grain yield at York in 2014 averaged 4.29 t ha⁻¹, but varied depending on variety ($P < 0.05$) and N fertiliser rate ($P < 0.05$; Figure 10).

Grain quality varied between the study sites, and between study years (Figures 11–16). In 2012 at Walebing, applying up to 75 kg N ha⁻¹ resulted in both varieties meeting the quality standards required for malting barley (Figure 12). No grain harvested at Cunderdin in 2012 met the quality standards for malting barley (Figure 11). By contrast in 2013, applying either 50 kg N ha⁻¹ (Cunderdin, Baudin; York, both barley varieties) or 75 kg N ha⁻¹ (Cunderdin, Buloke) produced acceptable malting barley quality (Figures 13 and 14). In 2014, at least 25 kg N ha⁻¹ needed to be applied at Wongan Hills, and 75 kg N ha⁻¹ to the York, to ensure the grain was classed as malting barley (Figures 15 and 16).

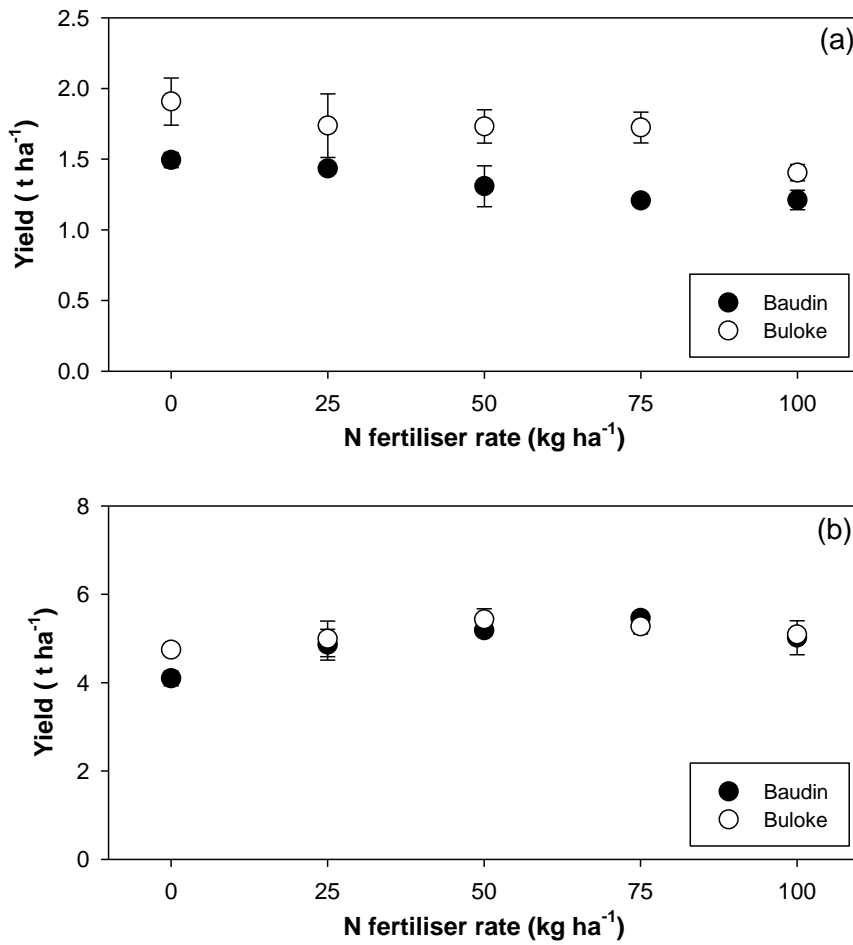


Figure 8. Grain yield response to varying N fertiliser application rates for two varieties of barley grown in the Western Australian grain belt at Cunderdin (a) and Walebing (b) in 2012. Values represent means (and standard errors) of three values. Note difference in y-axis scales.

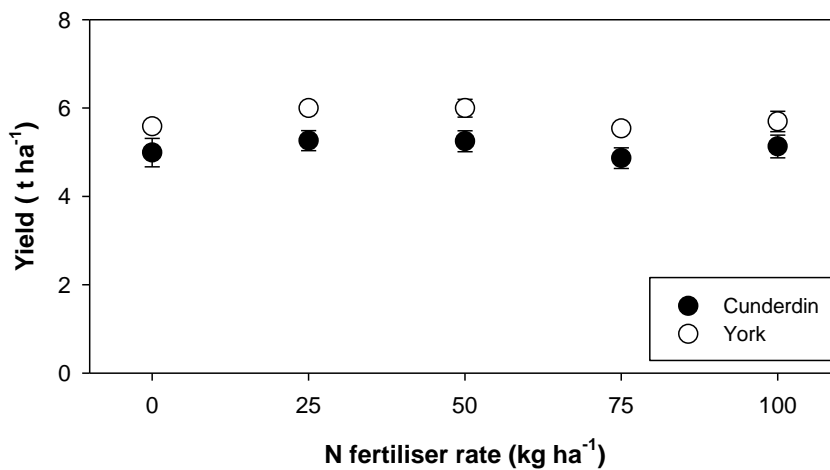


Figure 9. Grain yield response to varying N fertiliser application rates (averaged across variety) at Cunderdin and York in 2013. Values represent means (and standard errors) of six values.

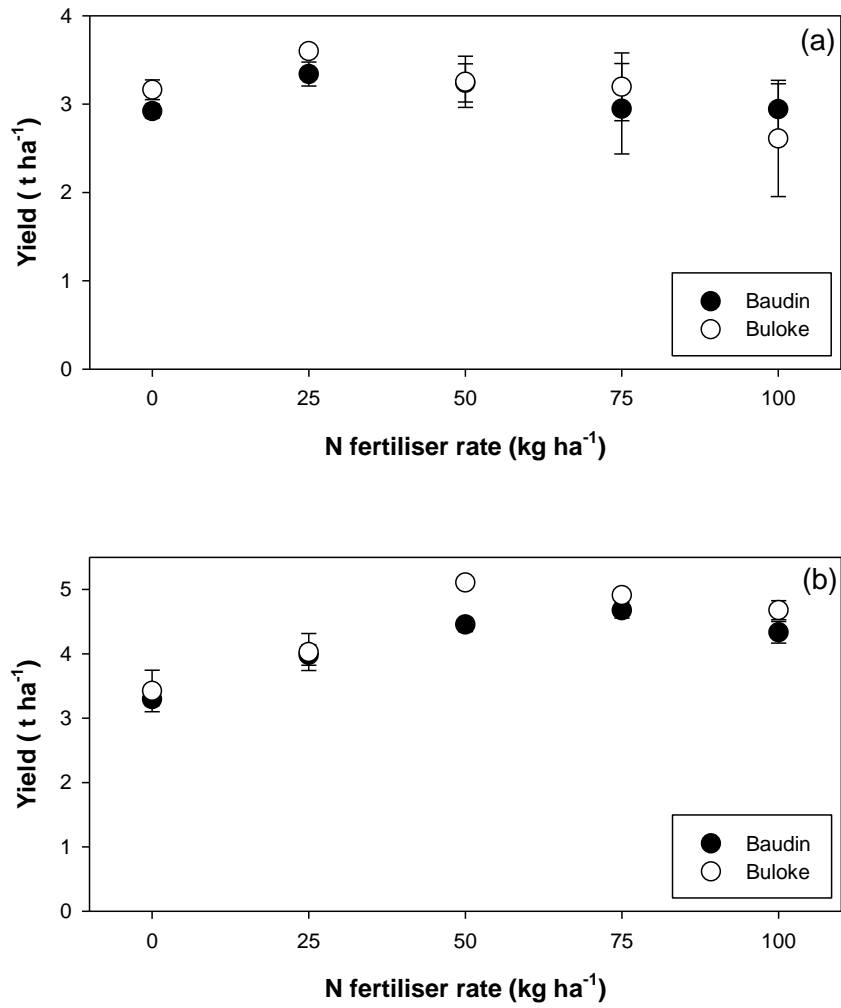


Figure 10. Grain yield response to varying N fertiliser application rates at Wongan Hills (a) and York (b) in 2014. Values represent means (and standard errors) of six values. Note difference in y-axis scales.

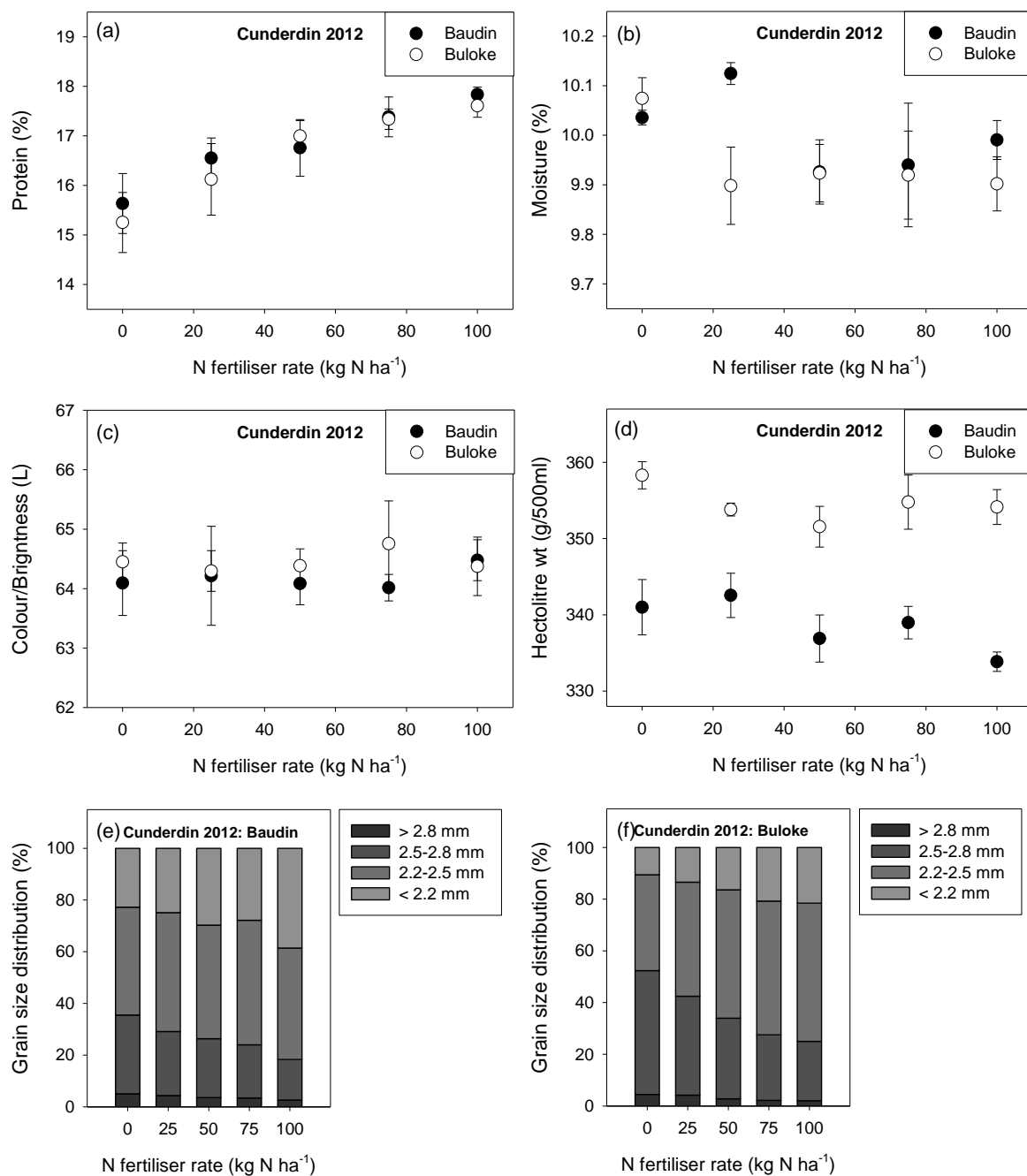


Figure 11. Grain quality parameters for barley at the Cunderdin research site in 2012. Quality standards for malting barley: Protein, 9–12.8%; Moisture, $\leq 12.5\%$; Colour (L) ≥ 55 ; Hectolitre weight ≥ 310 g/ 500mL; Grain size, contains $\leq 25\%$ grain that is < 2.5 mm. Quality standards are based on CBH 2012/13 Malting Barley Receival Standards. Values are means (and standard errors) of three values.

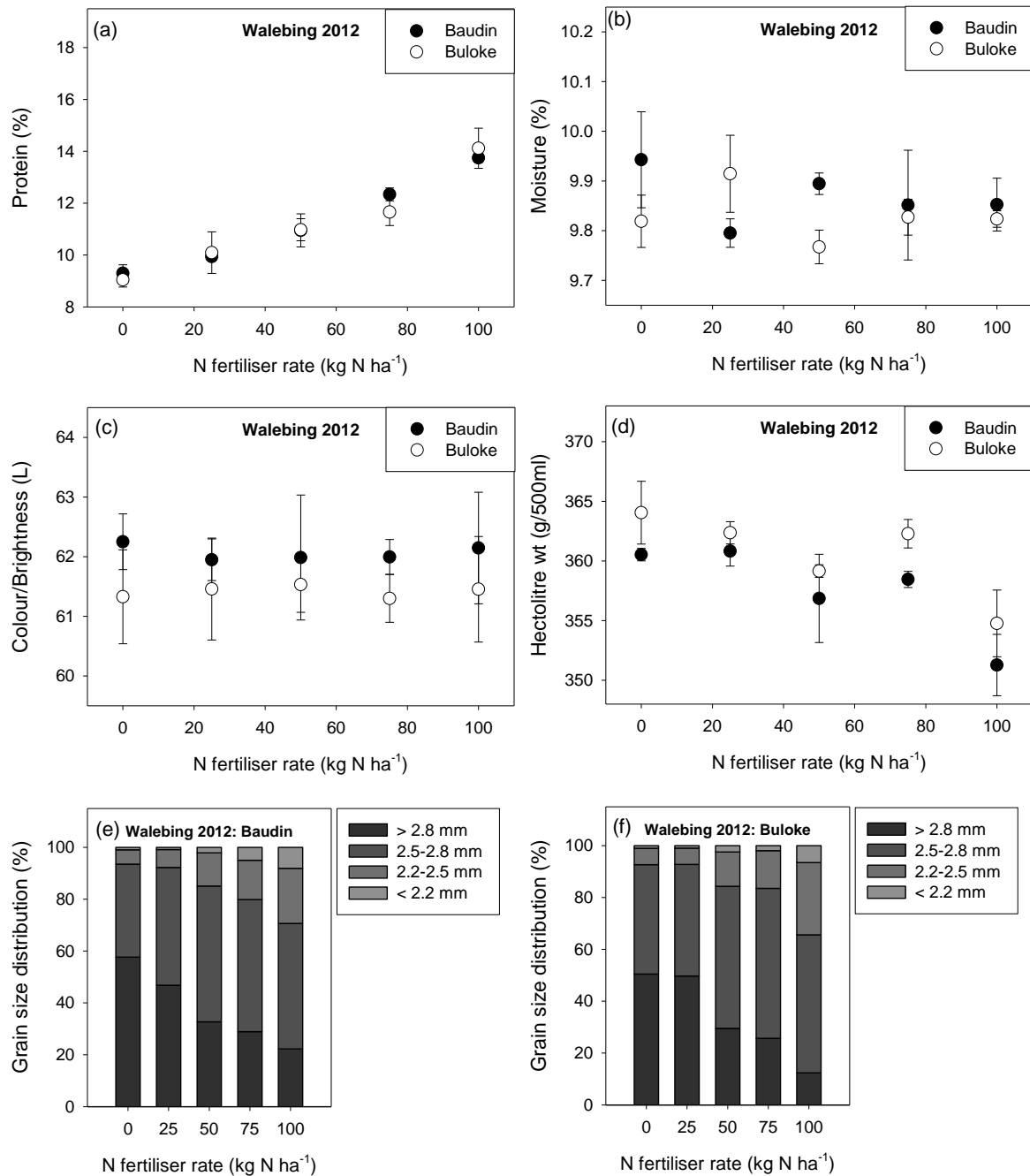


Figure 12. Grain quality parameters for barley at the Walebing research site in 2012. Quality standards for malting barley: Protein, 9–12.8%; Moisture, $\leq 12.5\%$; Colour (L) ≥ 55 ; Hectolitre weight ≥ 310 g/ 500mL; Grain size, contains $\leq 25\%$ grain that is < 2.5 mm. Quality standards are based on CBH 2012/13 Malting Barley Receival Standards. Values are means (and standard errors) of three values.

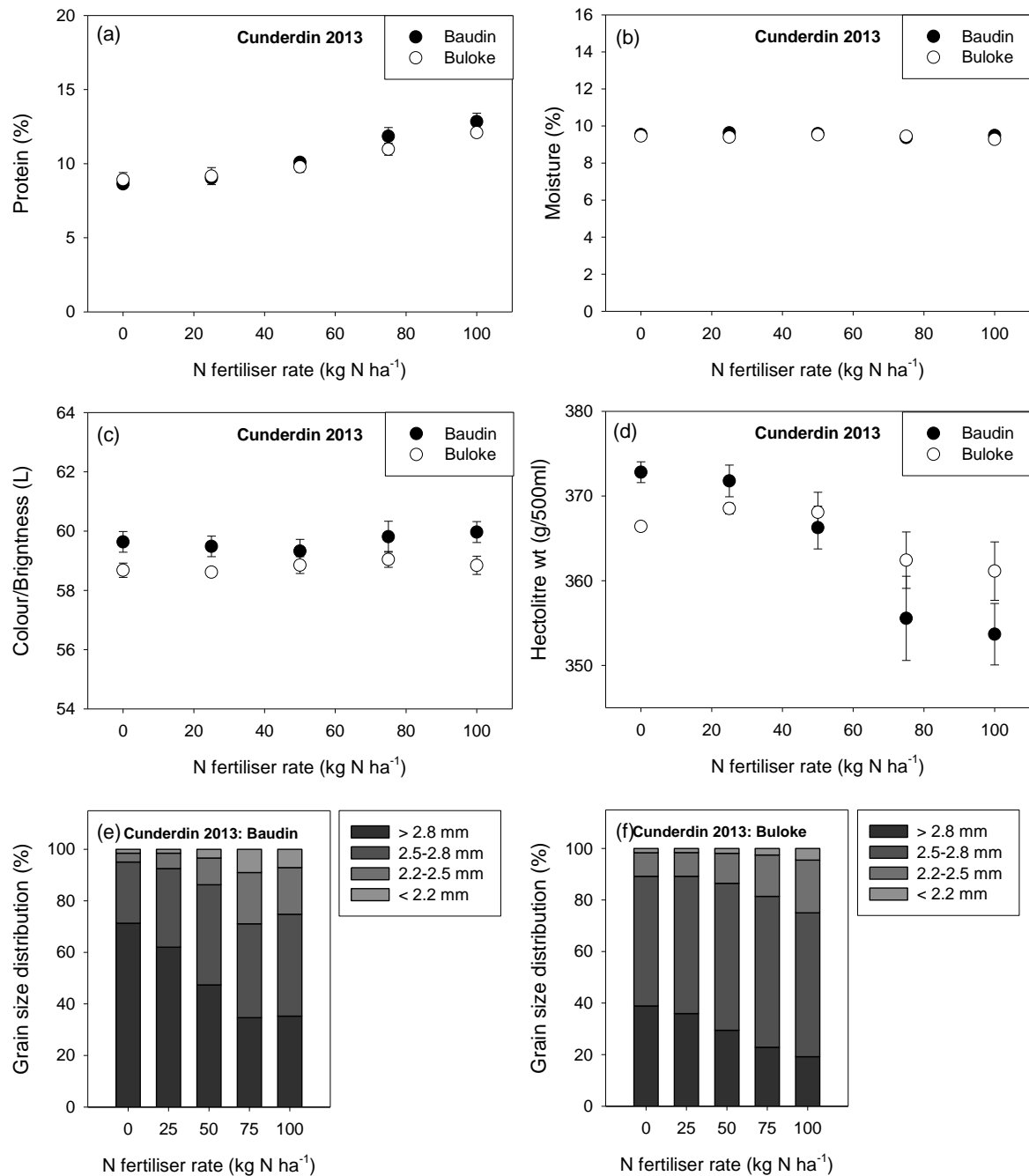


Figure 13. Grain quality parameters for barley at the Cunderdin research site in 2013. Quality standards for malting barley: Protein, 9.5–12.5%; Moisture, ≤12.5%; Colour (L) ≥ 56; Hectolitre weight ≥320 g/ 500mL; Grain size, contains ≤ 20% grain that is <2.5 mm. Quality standards are based on CBH 2013/14 Malting Barley Receival Standards. Values are means (and standard errors) of three values.

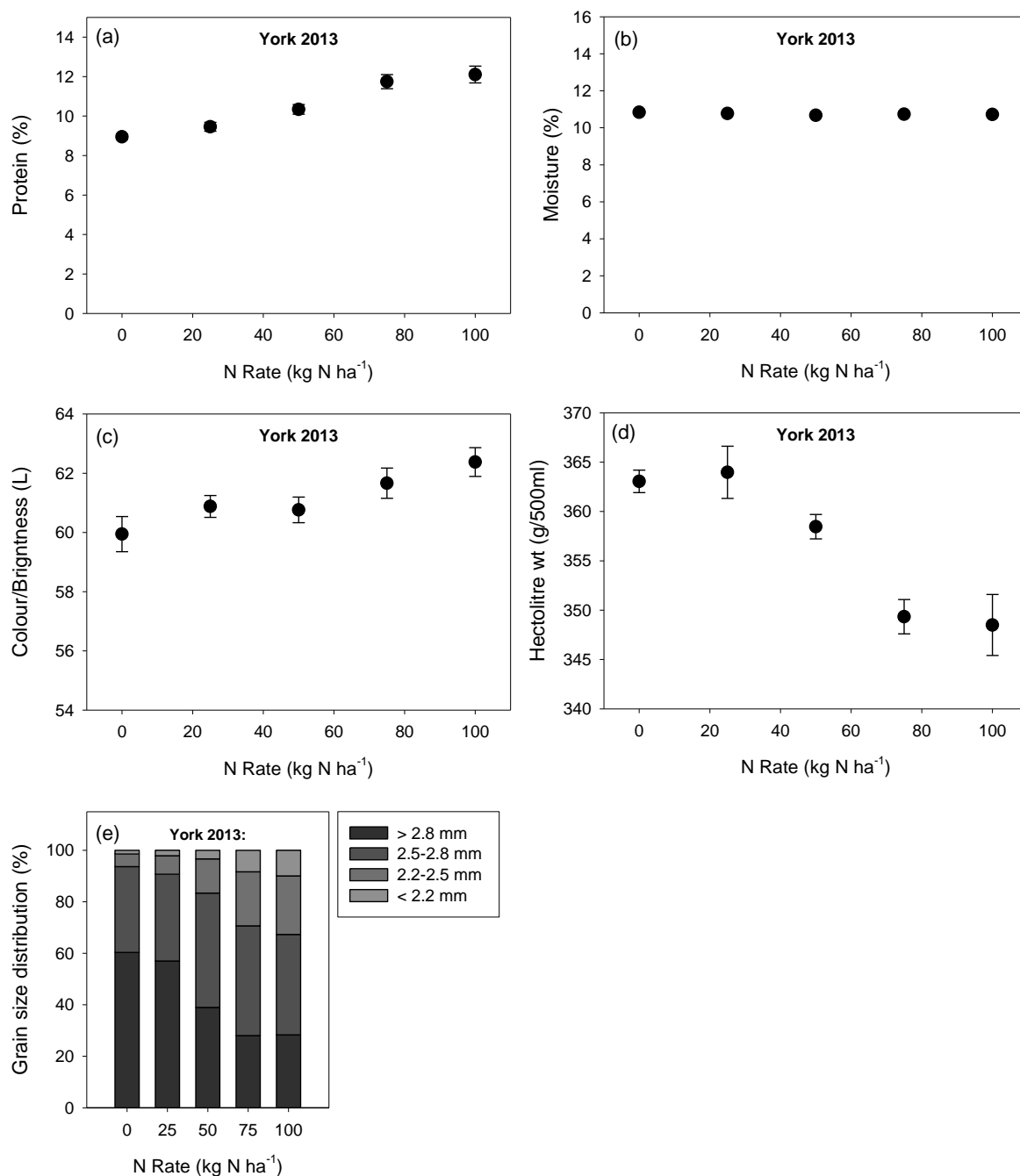


Figure 14. Grain quality parameters for barley at the York research site in 2013. Quality standards for malting barley: Protein, 9.5–12.5%; Moisture, $\leq 12.5\%$; Colour (L) ≥ 56 ; Hectolitre weight ≥ 320 g/ 500mL; Grain size, contains $\leq 20\%$ grain that is < 2.5 mm. Quality standards are based on CBH 2013/14 Malting Barley Receival Standards. Values are averaged across two barley varieties, and are means (and standard errors) of six values.

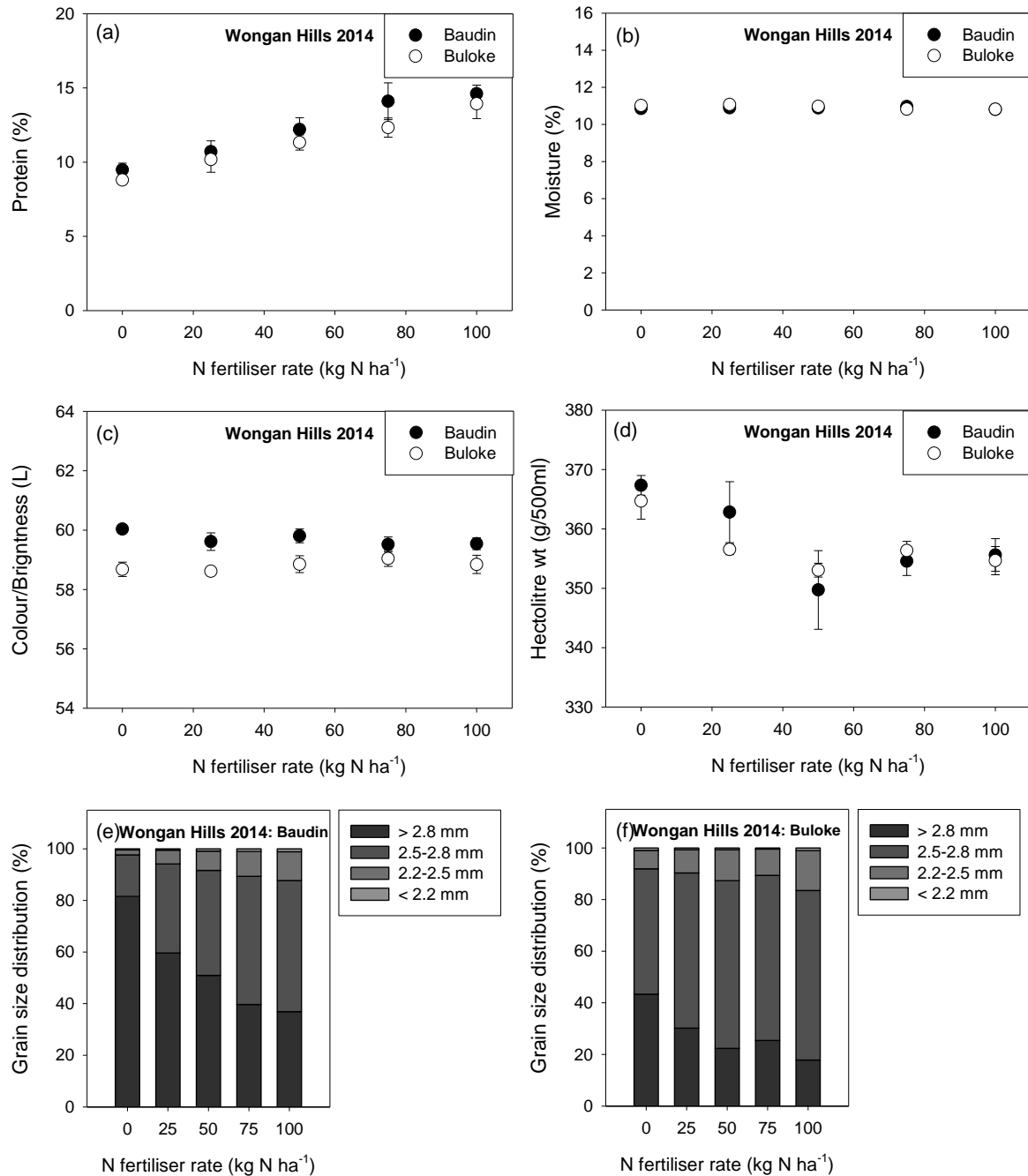


Figure 15. Grain quality parameters for barley at the Wongan Hills research site in 2014. Quality standards for malting barley: Protein, 9.5–12.5%; Moisture, $\leq 12.5\%$; Colour (L) ≥ 56 ; Hectolitre weight ≥ 320 g/ 500mL; Grain size, contains $\leq 20\%$ grain that is < 2.5 mm. Quality standards are based on CBH 2013/14 Malting Barley Receival Standards. Values are means (and standard errors) of three values.

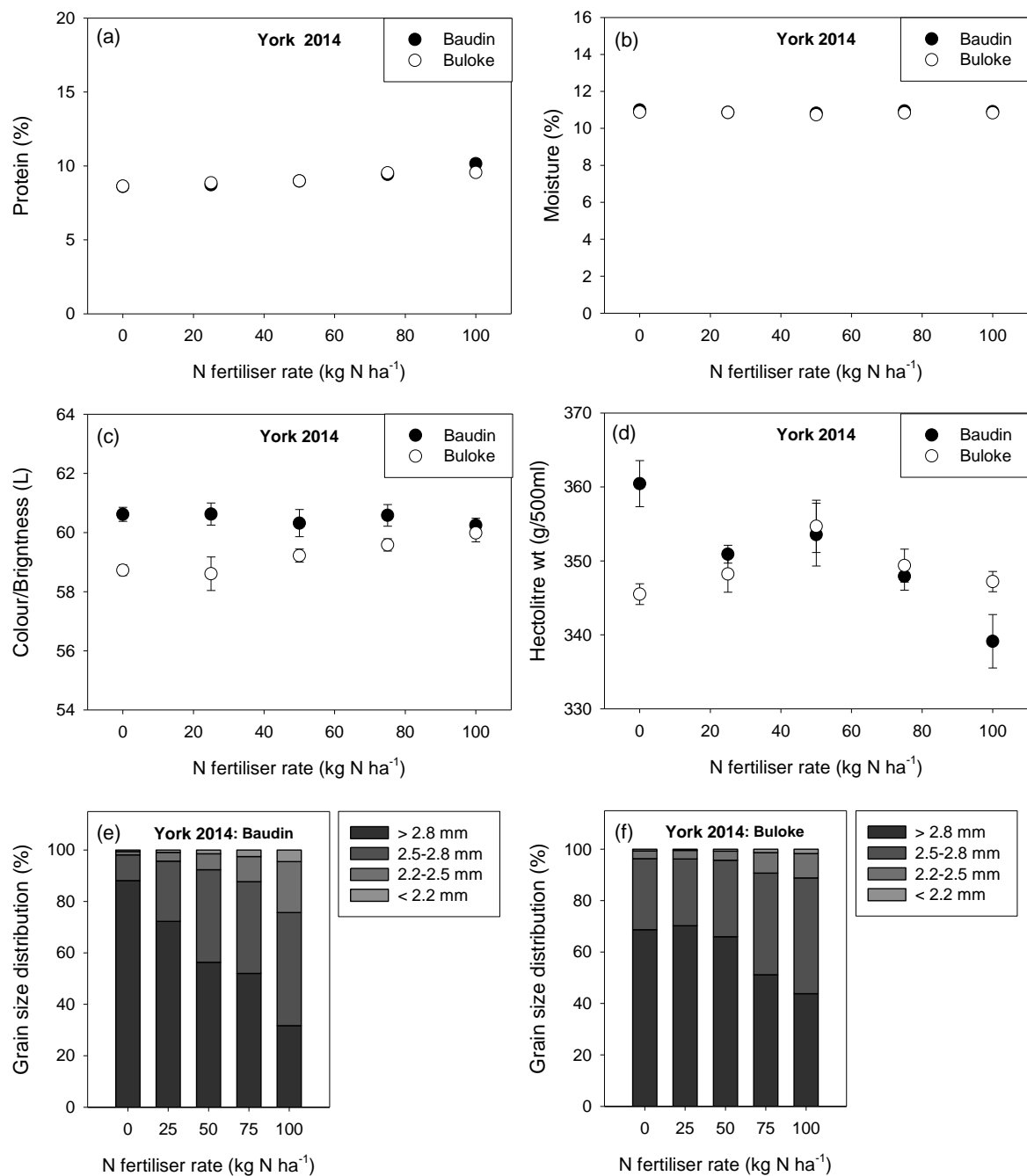


Figure 16. Grain quality parameters for barley at the York research site in 2014. Quality standards for malting barley: Protein, 9.5–12.5%; Moisture, ≤12.5%; Colour (L) ≥ 56; Hectolitre weight ≥320 g/ 500mL; Grain size, contains ≤ 20% grain that is <2.5 mm. Quality standards are based on CBH 2014/15 Malting Barley Receival Standards. Values are means (and standard errors) of three values.

Discussion

Soil organic carbon and greenhouse gas fluxes

Applying additional crop residues, and increasing SOC altered N₂O and CH₄ fluxes nine years after the regular addition of OM to a sandy soil commenced.

Nitrous oxide

Increasing SOC increased cumulative soil N₂O emissions 10-fold in the present study when N fertiliser was applied. Our findings are consistent with various global meta-data analyses demonstrating N₂O emissions from upland agricultural soils tend to increase in response to increasing SOC (Stehfest and Bouwman, 2006) by the addition of straw (Chen et al., 2013; Lehtinen et al., 2014; Liu et al., 2014). It has been argued that by increasing SOC the soil biological sources of N₂O, nitrification and denitrification, are in turn stimulated. Our companion study using soil collected from the present study site in part confirms these global observations. Utilising ¹⁴C and ¹⁵N techniques, Fisk et al. (2015b) demonstrated that while crop residue additions increased organic N retention by up to 2.8 times at the Buntine study site, it also increased inorganic N supply (mineralisation) and potential N loss pathways via nitrification to a similar extent; in-turn increasing the risk of N gaseous and leaching losses. The authors concluded crop residue additions to coarse textured soils are likely to increase the risk of N₂O emissions by up-regulating the entire soil N cycle (Fisk et al., 2015b).

Nitrous oxide emissions were low from a coarse textured, cropped soil in the Western Australian grain belt even with the addition of crop residues. This result is not unexpected as the greatest N₂O losses in response to crop residue incorporation tends to occur in heavier textured soils containing >10% clay (Chen et al., 2013). Consequently, the range of annual N₂O emission (0–0.15 kg N₂O-N ha⁻¹ yr⁻¹) in the present study were conservative in comparison to values reported for other cropped sites in Australia and overseas. Globally, and across a variety of climatic regions, annual N₂O losses from cropped mineral soils have ranged from 0.3 to 16.8 kg N₂O-N ha⁻¹ yr⁻¹ (Stehfest and Bouwman, 2006). The annual N₂O emission reported for Buntine was also within the range of values previously reported for other cropped soils in the Western Australian grain belt (Table 10). Furthermore, and in the absence of crop residue and N fertiliser additions, the soil progressively became a sink for N₂O emissions, which is consistent with findings from other soils containing low amounts of mineral N (Rosenkranz et al., 2006).

The greatest risk of N loss via N₂O emissions occurred in response to summer and autumn rainfall. This is consistent with previous observations for semi-arid soils, where a large proportion of annual N₂O emissions has occurred between crop growing seasons, when the soil was fallow, and in response to soil wetting following rainfall (Barton et al., 2008; Galbally et al., 2008). Elevated N₂O emissions following summer and autumn rainfall have been attributed to the rapid release of readily decomposable organic matter to viable microorganisms following wetting of dry soil (van Gestel et al., 1993). These substrates can be derived from nonliving organic matter already present in the soil, and from the death of microorganisms due to rapid changes in water potential (Kieft et al., 1987; Groffman and Tiedje, 1988; Schimel et al., 2007). Soil wetting also increases the diffusion of substrates and the mobility of microorganisms utilising those substrates (Borken and Matzner, 2009), and can decrease soil aeration (via increased soil water content and CO₂ respiration) sufficiently to promote denitrification (Barton et al., 2013b). In the present study increased soil water content and dissolved organic C coincided with elevated N₂O emissions (compare Figures 1

and 2) following summer and autumn rainfall, indicating a number of mechanisms could be responsible for the losses.

Methane

Increasing soil C contents in the surface soil has also decreased CH₄ uptake. Both CH₄ production and CH₄ uptake (oxidation) can occur in soil, and so CH₄ fluxes from soils are a product of the balance (Le Mer and Roger, 2001; Dalal et al., 2008). The effect of adding crop residues to upland cropping soils has not been studied extensively, with more attention given to ‘paddy’ soils (Liu et al., 2014). In the present study, we hypothesise increasing soil C increased CH₄ production relative to uptake, although the exact mechanism is not clear. It is also possible that the increase in soil C content may have decreased the rate at which air diffused through the surface soil, thus limiting CH₄ oxidation; but given the coarse texture of the soil this is unlikely. Instead, it is more likely that CH₄ oxidation has been inhibited by the increases in mineral N resulting from the OM additions (Le Mer and Roger, 2001). Interestingly, and in the absence of crop residue additions, CH₄ uptake has offset N₂O emissions. In another sandy cropped soil in the same region, CH₄ uptake was recorded, but did not necessarily offset N₂O emissions (Barton et al., 2013a; Barton et al., 2014). Further research is required to assess the extent of CH₄ uptake for soils throughout the grain belt of Western Australia.

Nitrous oxide emission factor for Australian dryland agriculture

Increasing soil C content in the present study has increased the N₂O emission factor for the application of N fertiliser in comparison to values previous reported for the Western Australian grain belt (compare Table 2 and Table 10). The emission factor may have also been further enhanced by applying N fertiliser above the district average, for experimental purposes, as emission factors tend to increase with an increasing rate of N fertiliser (Millar et al., 2010). The emission factor for the OM+tillage treatment (0.1%), however, was less than both the international default value (1.0%) (IPCC., 2006) and the value used by the Australian Government for dryland agriculture (0.3%). Our current, and past, research supports further lowering the emission factor for calculating N₂O emissions from the application of N fertiliser to non-irrigated, cropped soils in Australia’s semi-arid regions.

Table 10. Annual N₂O emissions from cropped soils in Western Australia.

Location, year	Crop	N application (kg N ha ⁻¹ yr ⁻¹)	Annual N ₂ O emission (kg N ha ⁻¹ yr ⁻¹)	Emission factor (%)
Cunderdin, 2005 [†]	Wheat	0	0.09	0.02
		100	0.11	
Cunderdin, 2006 [‡]	Wheat	0	0.07	0.02
		75	0.09	
Cunderdin, 2007 [§]	Canola	0	0.08	0.06
		75	0.13	
Cunderdin, 2008 [¶]	Lupin	0	0.13	NA
Wongan Hills, 2009 [#]	Lupin	0	0.04	NA
	Wheat	75	0.06	
Wongan Hills, 2010 [#]	Wheat	20	0.06	NA
	Wheat	50	0.07	

[†]Barton *et al.*(2008); [‡]Li *et al.*(2012); [§]Barton *et al.*(2010); [¶]Barton *et al.*(2011); [#]Barton *et al.* (2013a), only results for non-limed soils presented. NA, not applicable.

Increasing SOC in the surface soil via crop residue additions increased grain yield in the Northern grain belt of Western Australian, even in low rainfall years. At the same time, increasing soil C showed potential to lower the N fertiliser inputs required to meet grain quality standards. Our observations are consistent with international meta-analyses demonstrating how the incorporation of straw and crop residues into soil benefits crop yield with time as long it does not lower N availability by increasing soil N immobilisation (Lehtinen et al., 2014; Liu et al., 2014). Furthermore, our observed yield response to the crop residue additions is also consistent with yield responses previously recorded at the study site by the Liebe Grower Group (Figure 17).

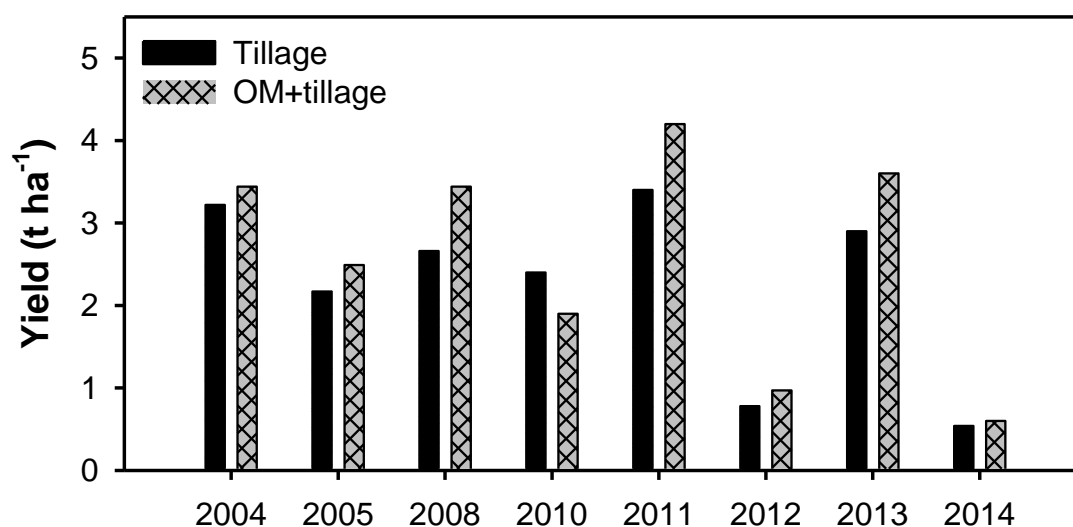


Figure 17. Historic cereal grain yields (t/ha) for OM+tillage and the Tillage treatments at the Liebe Group's Long Term Research Site. Data courtesy of the Liebe Group.

It is not clear why increasing SOC has increased grain yield in the present study. Others have attributed increased crop yield in response to increased SOC to improved soil nutrient availability (in particular N, P and K) and improved soil physical conditions, such as water-holding capacity (Liu et al., 2014). Although the incorporation of additional crop residues increased nutrient availability at the present study site, soil P and K were already sufficient in the non-amended soil (Tillage treatment). There was some indication that increasing SOC may have improved plant available N. For example in 2013, applying 25 kg N ha⁻¹ to the Tillage treatment increased indicators of yield potential at anthesis (i.e., grain head number, grain and dry matter production) to similar values measured in the OM+tillage treatment that did not receive N fertiliser, suggesting grain yield potential in the OM+tillage treatment benefited from additional N supplied by soil N mineralisation. However, the subsequent grain yield showed no response to N fertiliser additions for either OM treatment, which was also true for both yield potential and yield measurements in 2014. Increasing SOC could have also benefited grain yield by increasing water availability via increased soil water holding capacity; as demonstrated by small difference in soil water content at field capacity (Table 1). Irrespective of the mechanism, increasing SOC is likely to benefit grain yield from sandy, rain-fed cropping soils, even in low yielding years.

Mineralisation of SOC during the summer fallow is a significant source of plant available N in the Western Australian grain belt, and needs to be taken into account when predicting N fertiliser requirements. At some study sites we observed in excess of 60 kg N ha⁻¹ in the surface 60 cm of the soil at seeding; sufficient to produce 1.5 t ha⁻¹ of wheat without applying additional N fertiliser. The extent of soil mineralisation prior to seeding in the Western Australian grain belt depends upon the SOC content, but also soil water content and temperature (Murphy et al., 1998; Hoyle and Murphy, 2011; Fisk et al., 2015b). Consequently, the amount of soil mineralisation will not only vary from soil-to-soil, but also from year-to-year in response to summer rainfall. For example in 2013, and after 91 mm of rainfall at Buntine three months prior to seeding, there was 96 kg N ha⁻¹ (surface 60 cm) in the OM+tillage and 44 kg N ha⁻¹ in the Tillage at seeding; however in 2014, and after 65 mm of summer rainfall three months prior to seeding, plant available N in both OM treatments at seeding (55 kg N ha⁻¹, OM+tillage; 13 kg N ha⁻¹, Tillage) almost halved in comparison to 2013. Predicting the supply of mineral N from soil mineralisation is critical for optimising N fertiliser applications, however soil testing to determine SOC contents needs to be combined with a good understanding of the rates of soil mineralisation during the summer fallow.

Implications for managing N₂O emissions from Australian dryland agriculture

Land management practises that increase SOC in Western Australia's cropping soils should continue to be encouraged. Although increasing SOC increases the risk of N₂O emissions from cropped soils, these losses are likely to be relatively small from sandy-textured soils in the Western Australian grain belt.

Increasing SOC contents is expected to increase mineral N availability. Growers should therefore modify N fertiliser inputs to reflect changes in plant available N. Such practices have the potential to improve grain yield and profitability from sandy-textured soils, while minimising adverse losses such as soil N₂O emissions and N leaching. However, accounting for changes in the amount and timing of plant available N in response to increased SOC requires an understanding of soil N mineralisation rates, and the associated regulating factors. Both net and gross mineralisation rates have been measured in cropping soils of Western Australia, and rates incorporated in local decision support models for predicting N fertiliser requirements (e.g., Select Your Nitrogen, Yield Profit). The success of these models to accurately predict soil N mineralisation rates appears to be largely untested. Ultimately, improved soil N management is essential if the benefit of increased carbon storage for the purposed of mitigating global warming mitigation is to be fully realised.

Opportunities for decreasing the risk of N₂O loss following summer and autumn rainfall events in the Western Australian grain belt are limited. Developing strategies for mitigating N₂O emissions from semi-arid cropping regions is more challenging than for temperate climates, as losses occur post-harvest, when there is no active plant growth, and not in direct response to N fertiliser additions (e.g., Barton et al., 2008; Galbally et al., 2008). Strategies that control soil N supply from nitrification, or immobilise excess inorganic N via soil microbial or plant uptake, would be expected to decrease the availability of N for subsequent N₂O loss in semi-arid regions. Indeed, previous studies have demonstrated increasing the efficiency of the nitrification process by increasing soil pH (via liming) could in turn decrease N₂O losses from sandy, acidic soils following summer rain (Barton et al., 2013b; Barton et al., 2013a). A laboratory-based study also suggested nitrapryin, a nitrification inhibitor, may also have the potential to limit N₂O losses in the study region (Fisk et al., 2015a); but requires field-based verification. Controlling the supply and immobilisation of inorganic N through

the incorporation of crop residues has proven to be difficult in the Western Australian grain belt (Hoyle and Murphy, 2011; Fisk et al., 2015b). Instead, the presence of root exudates has been shown to be more effective at increasing microbial N immobilisation relative to N supply (nitrification) than long term additions of crop residues (Fisk et al., 2015b). The potential for plants to both utilise mineral N and stimulate soil N immobilisation during the summer fallow warrants further attention in Australian dryland cropping systems.

Key Findings

Growers should continue to be encouraged to employ land management practises that increase SOC in Western Australia's cropping soils. Increasing soil C benefits crop production, and has the potential to decrease N and other fertiliser needs. Although increasing SOC increased soil N₂O emissions (and inhibited CH₄ uptake) in the present study, these losses were relatively low.

The greatest risk of N₂O emissions from a sandy soil in the Western Australian grain belt occurred in response to summer-autumn rainfall events, and more so with increasing SOC. This observation is consistent with previous observations for semi-arid soils where a large proportion of annual N₂O emissions occurred between crop growing seasons, when the soil was fallow, and in response to soil wetting following summer and autumn rainfall. Approaches to decreasing N₂O emissions following summer rainfall events is limited to decreasing N₂O emissions from nitrification (e.g., liming, nitrification), and increasing soil N immobilisation and plant N uptake during summer and autumn.

Nitrogen supply (via mineralisation) prior to seeding varied depending on soil type and summer rainfall, and needs to be included when determining annual N fertiliser requirements. Optimising N fertiliser input will increase farm profitability and decrease the risk of N₂O emissions arising from under-utilised N fertiliser.

The proportion of N fertiliser applied that was lost as N₂O from a sandy soil in the Western Australian grain belt ranged from 0.08 to 0.12%. This finding, plus past research in the Western Australian grain belt, supports further lowering current Australia's emission factor (0.3%) for calculating N₂O emissions from the application of N fertiliser to non-irrigated, cropped soils in Australia's semi-arid regions.

Future Research Needs

A number of studies (Lam et al., 2013; Luo et al., 2014) have examined the extent to which agricultural management practices can increase SOC in Australia's cropping soils. These findings should be combined with current modelling efforts to assess the impact on national N₂O emissions and grain production.

Accurately predicting the supply of mineral N from soil mineralisation is critical if the benefit of increased carbon storage for the purpose of mitigating global warming mitigation is to be fully realised. The ability of current decision support models to accurately predict soil N mineralisation rates, and assist agronomists and growers to optimise N fertiliser inputs, requires further investigation under Australian cropping scenarios.

The extent of CH₄ uptake in agricultural soils has largely been ignored (Dalal et al., 2008). The present study indicates that there are situations whereby CH₄ uptake may offset other GHG emissions. Future work should review our current understanding of CH₄ uptake in Australian cropping soils, including the effects of agricultural management practises and soil types, and then determine if further field-based research is warranted.

Practical approaches are required to minimise N₂O emissions from Australian dryland cropping soils following summer and autumn rainfall. The potential for plants to both utilise mineral N and stimulate soil N immobilisation during the summer fallow warrants further attention in Australian dryland cropping systems.

Publications

A communication strategy for this research project was developed in collaboration with National Agricultural Nitrous Oxide Emissions Research in Australia Program (NANORP), the Grains Research Development Corporation (GRDC), the Department of Agriculture and Food WA (DAFWA), and the Liebe Group. Growers and agribusiness were informed of the project objectives and findings via a website (<http://www.n2o.net.au/>), publications in industry journals, participation in industry workshops and national conferences, plus field days and research site visits throughout the project. Australian researchers and representatives from the Department of Agriculture (DA) and GRDC were kept informed of project progress and findings at twice yearly NANORP and annual GRDC 'More Profit from Crop Nutrition II' Project Leader workshops. Researchers and policy makers were informed of project outcomes via scientific conferences and publications at the completion of the project. The UWA Research Staff had the main responsibility of disseminating research findings to industry groups. However other project team members, including the Department of Agriculture and Food WA and the Liebe Group, also disseminated project findings to growers and agribusiness.

Publications and presentations produced during the project are listed below. Those marked with an asterisk have been compiled and attached to the Final Progress Report.

Industry Articles, Newsletters, Podcasts and Media Releases

- *Barton, L. 2012. Why measure soil nitrous oxide emissions? Liebe Group Newsletter, August 2012, Volume 15 (Issue 6), page 7.
- *A press release "How much of your urea turns into gas?" was prepared by the Liebe Grower group, approved by DA and distributed to the following local newspapers and newsletters in November 2012: Dalwallinu Community Newspaper, Kalannie Kapers, Carnamah Community Newspaper, Perenjori Bush Telegraph, Koora Community Newspaper, Coorow Magpie Squark, Miling School Newsletter, Wongan Ballidu Boomer.
- *Barton L., F. Hoyle, and D. Murphy. 2013. Does increasing soil carbon in sandy soils increase soil nitrous oxide emissions from grain production? In: *Local Research and Development Results: Results for 2012 season*. Pages 135–137. Published and distributed by the Liebe Group to approximately 150 growers and industry representatives in the Northern Grain Belt of Western Australia each year.
- *Maccarone, L., L. Fisk, Y. Sawada, L. Barton, D. Gleeson, and D. Murphy. 2013. Determining nitrogen dynamics in semi-arid soil. In: *Local Research and Development Results: Results for 2012 season*. Pages 138–140. Published and distributed by the Liebe Group to approximately 150 growers and industry representatives in the Northern Grain Belt of Western Australia each year.
- *A press release "Soil carbon study to test nitrogen gas risk" was prepared by The University of Western Australia, approved by DA, and distributed to a number of media outlets including rural newspapers in February 2013.
- *Barton, L. 2013. Investigating the effect of increasing soil carbon on nitrous oxide emissions from the Long Term Soil Biology Trial. Liebe Group Newsletter, August 2012, July 2013, Volume 16 (Issue 5), pages 14–15.
- *'Spotlight on soil carbon and nitrogen fertiliser'. GRDC Ground Cover, July-August 2013, p42.

- *Barton L., D. Murphy, and F. Hoyle. 2014. Does increasing soil carbon in sandy soils increase soil nitrous oxide emissions from grain production? In: *Local Research and Development Results: Results for 2013 season*. Pages 114–117. Published and distributed by the Liebe Group to approximately 150 growers and industry representatives in the Northern Grain Belt of Western Australia each year.
- *Barton L., D. Murphy, F. Hoyle, and C. Scanlan. 2014. Does increasing soil carbon in sandy soils effect N fertiliser requirements and grain production? In: *Local Research and Development Results: Results for 2013 season*. Pages 118–122. Published and distributed by the Liebe Group to approximately 150 growers and industry representatives in the Northern Grain Belt of Western Australia each year.
- Barton, L. 2015. How much N is in the soil? <https://youtube/pGy13BBUJqY>. Published on 14 January 2015.
- *Barton L., D. Murphy, and F. Hoyle. 2015. Does increasing soil organic carbon in sandy soils increase soil nitrous oxide emissions from grain production? In: *Local Research and Development Results: Results for 2014 season*. Pages 122–125. Published and distributed by the Liebe Group to approximately 150 growers and industry representatives in the Northern Grain Belt of Western Australia each year.
- *Smith, F. 2015. The cost of climate friendly lupins measured. GRDC Ground Cover, March-April, page 19.
- Baxter, N. 2015. Researchers probe impacts of increased soil organic carbon. GRDC Ground Cover, June-July, page 19. An associate podcast was also produced, and can be viewed at <https://youtu.be/ojhF43zMhGU>.

Field Days and other Grower Engagements

- Barton, L. 2012. Soil N₂O emissions from cropped soils in WA. Presentation at ‘Get the Dirt on Soil Carbon’ workshop organised by the Department of Agriculture, Fisheries and Forestry, Northam (Western Australia), 22 June.
- Barton, L. 2012. Project aims and approach presented to growers at the Western Australian No Tillage Association (WANTFA) spring field day, Cunderdin (Western Australia), 4 September. Presentation was at the Cunderdin field site described above. Approximately 270 people attended the event, including growers, scientists and representatives from GRDC. Attendees received a booklet that included summaries of the projects presented at the field day.
- Barton, L., and D. Donovan. 2012. Project aims and approach presented to GRDC’s Western Panel, Buntine (Western Australia), 12 September. Presentation at the Buntine field site (described above) and the panel could inspect the automated chamber system.
- Hoyle, F., and D. Donovan. 2012. Project aims and approach presented to growers at the Liebe Growers Group “On The Sand Plain and Controlled Traffic Field Walk”, Buntine (Western Australia), 26 September. Presentation at the Buntine field site (described above) with attendees able to inspect the automated chamber system.
- Davies, S., C. Gazey, F. Hoyle, and C. Scanlan, 2013. Six technical workshops ‘Get to know your soils deeper’ integrating the latest work on crop nutrition, soil biology, soil acidity, soil water repellence and crop nutrition were conducted in 2013. The workshops were led by our Industry Partner (F. Hoyle, C. Scanlan; DAFWA) who presented information on crop N responses. Workshops were held throughout the Western Australian grain belt: Northam (27 June), Badgingarra (23 July), Mingenew (6 August), Wongan Hills (7 August), Wickepin (14 August), and Gnowangerup (15 August). Agronomist, consultants and growers were the target audience.

- Barton, L. 2013. Project aims and approach of the study outlined in an interview with ABC Regional Radio (WA Mid West and Wheatbelt). The interview was broadcast on Monday 26 August 2013.
- Barton, L. 2013. Project aims and approach presented to growers at the Western Australian No Tillage Association (WANTFA) spring field day, Cunderdin (Western Australia), 4 September. Presentation was at the Cunderdin field site described above. Approximately 250 people attended the event.
- Barton, L. 2014. Project results discussed with growers at the “Liebe Group 2013 Trials Review Day”, 18 February, Dalwallinu.
- Barton, L. 2014. “Nitrous oxide emissions from WA cropping soils: A review of sub-daily emissions and findings”. Presented at the inaugural Carbon Farming Network meeting, coordinated as part of the WANTFA Carbon Farming Extension and Outreach Project, 28 March, Floreat, Western Australia.
- Davies, S., C. Gazey, F. Hoyle, and C. Scanlan. 2014. Five technical workshops ‘Get to know your soils deeper’ integrating the latest work on crop nutrition, soil biology, soil acidity, soil water repellence and crop nutrition were conducted in 2014. The workshops were led by our Industry Partner (F. Hoyle, C. Scanlan; DAFWA) who presented information on crop N responses. Workshops were held throughout the Western Australian grain belt: Esperance (27 June), Corrigin (30 July), Ravensthorpe (1 July), Lake Grace (2 July), and Katanning (3 July). Agronomist, consultants and growers were the target audience.
- Hoyle, F., and L. Barton. 2014. ‘Soil Biology Trial: 2003–2014 results’. Presented at the Liebe Group Field Walk, 27 July 2014. Presentation was attended by growers (30) and industry representatives (5) at an event coordinated by the Liebe Group. Findings from the present study were included in the presentation.
- Barton, L. 2014. ‘Does increasing soil organic matter increase nitrous oxide emissions from cropped soils?’ Presented at the WANTFA Long Term Cropping Systems and Soils Day, 25 September, Cunderdin.
- Barton, L., C. Scanlan, F. Hoyle, D. Murphy. 2015. ‘Increasing soil organic carbon increases soil N: Implications for crop production on sandy soils?’ Presented at Crop Updates, 4 March, Dalwallinu Recreation Centre, Dalwallinu. The event was attended by growers (52) and industry representatives (46), and coordinated by the Liebe Group.

Scientific Publications

- *Barton, L., D.B. Gleeson, L.D. Maccarone, L.P. Zúñiga, and D.V. Murphy. 2013. Is liming soil a strategy for mitigating nitrous oxide emissions from semi-arid soils? *Soil Biology and Biochemistry* 62, 28–35.
- *Barton, L., D.V. Murphy, and K. Butterbach-Bahl. 2013. Influence of crop rotation and liming on greenhouse gas emissions from a semi-arid soil. *Agriculture, Ecosystems and Environment* 167, 23–32.
- *Barton, L., T. Thamo, D. Engelbrecht and W. Biswas. 2014. Does growing grain legumes or applying lime cost effectively lower greenhouse gas emissions from wheat production in a semi-arid climate? *Journal of Cleaner Production* 83, 194–203.
- Barton, L., B. Wolf, D. Rowlings, C. Scheer, R. Kiese, P. Grace, K. Stefanova, and K. Butterbach-Bahl. 2015. Sampling frequency affects estimates of annual nitrous oxide fluxes. *Nature Scientific Reports (submitted)*.

- *Fisk, L., L. Barton, D.L. Jones, H.C. Glanville, and D.V. Murphy. 2015. Root exudate carbon was more effective than soil organic carbon at decreasing the risk of nitrogen loss in a semi-arid soil. *Soil Biology and Biochemistry* (in press).
- *Fisk, L., L.D. Maccarone, L. Barton, and D.V. Murphy. 2015. Nitrapyrin decreased nitrification of nitrogen released from soil organic matter but not amoA gene abundance at high soil temperature. *Soil Biology and Biochemistry* 88, 214–223.

Scientific Conferences and Workshops

- Barton, L. 2012. Project update presented at the bi-annual NANORP Meeting, 15 August 2012, Melbourne.
- *Barton, L., W. Biswas, K. Butterbach-Bahl, T. Thamo, D. Engelbrecht, and D. Murphy. 2012. Assessing strategies for mitigating greenhouse gas emissions from wheat production: Role of grain legumes and soil liming. Presented at the CCRSPI Conference, 27–29 November, Melbourne.
- *Barton, L., K. Butterbach-Bahl, and D.V. Murphy. 2012. Does cropping rotation and liming affect greenhouse gas emissions from a semi-arid soil? Presented at the Joint Australian and New Zealand Soil Science Conference, 2–7 December, Hobart.
- Barton, L. 2013. Project update presented at the bi-annual NANORP Meeting, 13–14, February, Camden.
- Barton, L. 2013. Project update presented at the annual GRDC More Profit from Crop Nutrition II program meeting, 16–18 April, Adelaide.
- Barton, L. 2013. Project update presented at the bi-annual NANORP Meeting, 21–22 August, Canberra.
- *Barton, L., D.V. Murphy, T. Thamo, W. Biswas, D. Engelbrecht, K. Butterbach-Bahl. 2013. Does growing grain legumes or soil liming lower greenhouse gas emissions from wheat production in a semi-arid climate? Presented at the ASA, CSA and SSSA International Annual Meeting, Tampa (Florida), USA, 3–6 November.
- Barton, L. 2014. Project update presented at the bi-annual NANORP Meeting, 12–13 February, Brisbane.
- Barton L. 2014. Project update presented at the annual GRDC More Profit from Crop Nutrition II program meeting, 1–3 April, Perth.
- *Barton, L., C. Scanlan, B. Bowden, F. Hoyle, B. Paynter, and D. Murphy. 2014. Predicting soil mineral supply for cropping production. Crop Nutrition Symposium, 9 June, Murdoch University, Perth.
- *Murphy, D.V., L. Barton, D. Donovan, L.D. Maccarone, N.C. Banning, X. He, J. Zhou, S. Pu, Y. Yin, M. Xu, D.B. Gleeson, and D.L. Jones. 2014. Biochar did not alter nitrous oxide emissions from a semiarid agricultural soil – Alternative mitigation strategies are required. 4th International conference on C sequestration and climate change mitigation in agriculture, 21–24 September, Yangling, China.
- *Barton, L., B. Wolf, D. Rowlings, K. Butterbach-Bahl, K. Stefanova, P. Grace, C. Scheer, and R. Kiese. 2014. Effect of sampling frequency on estimates of annual nitrous oxide fluxes. Presented at the ASA, CSA and SSSA International Annual Meeting, Long Beach (California), USA, 2–5 November.
- *Barton, L., F. Hoyle, and D.V. Murphy. 2014. Does increasing soil carbon in sandy soils increase soil nitrous oxide emissions from grain production? Presented at the National Soil Science Conference, Soil Science Australia, Melbourne, 23–27 November.
- *Bell, M., L. Barton, G. Schwenke, R. Harris, R. Armstrong, and L. Guangdi. 2014. Reducing N₂O emissions and associated nitrogen emissions from grain-growing soils

of Australia. Presented at the National Soil Science Conference, Soil Science Australia, Melbourne, 23–27 November.

- *Barton, L., F.C. Hoyle, and D.V. Murphy. 2014. ‘Does increasing soil carbon in sandy soils increase soil nitrous oxide emissions from grain production? Poster presented at the bi-annual NANORP Meeting, 27 November, Melbourne.
- Barton, L. 2015. Final project update presented at the annual GRDC More Profit from Crop Nutrition II program meeting, 7–9 April, Brisbane.
- Barton, L. 2015. Final project update presented at the bi-annual NANORP Meeting, 14–15 July, Canberra.
- Barton, L. 2015. Nitrous oxide emissions from arable agriculture in a semi-arid region. Presented (invited speaker) at *Transitioning Cereal Systems to Adapt to Climate Change*, Minneapolis (Minnesota), USA, 11–13 November.
- Barton, L., F.C. Hoyle, and D.V. Murphy. 2015. ‘Does increasing soil carbon increase soil nitrous oxide emissions from grain production in a semi-arid region? Presented at the ASA, CSA and SSSA International Annual Meeting, Minneapolis (Minnesota), USA, 15–18 November.

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